11. ELLIOTT BAY AND THE DUWAMISH RIVER ESTUARY

11. ELLIOTT BAY AND THE DUWAMISH RIVER ESTUARY

This section presents an assessment of the Duwamish Estuary and Elliott Bay, focusing on its transformation from a natural system to a highly modified, urban estuary and bay. Over the past century, the Duwamish Estuary and Elliott Bay have undergone substantial changes as the area developed into an industrial seaport and urban center. Before 1906, the large, unregulated freshwater outflow of the original Duwamish River built and maintained a large and relatively dynamic estuary in the lower Duwamish Valley. The hills now occupied by Seattle and West Seattle originally constrained the river delta. Based on early maps, the estuary was characterized by a sinuous channel and several distributaries (Blomberg et al. 1988). These stream channels would have been constantly changing, as is typical of a low-gradient river with substantial periodic sediment-laden flood flows.

Beginning as early as 1895, tideflats and saltmarshes along the Duwamish River and the Seattle waterfront were filled with soil cut from hilly areas to the east and with sediments dredged to create protected harbor areas. In the early 1900s, the natural estuary was greatly modified by the construction of Harbor Island, the East and West Waterways, and the Duwamish shipping channel. Creation of the waterways resulted in the replacement of 9.3 mi of meandering river with the 5.3-mi straightened channel that exists today (Blomberg et al. 1988). The transformation of the natural estuarine system into its present navigation channel is illustrated in Table 44 and Figure 21 (Blomberg et al. 1988; Bortleson et al. 1980).

A synthesis of information and data on existing conditions within the nearshore of the Duwamish Estuary and Elliott Bay is presented and data gaps are identified. For the purposes of this report, Elliott Bay is defined as the nearshore area extending from Alki Point to West Point. The Duwamish Estuary is defined as the lower river from the mouth to river mile (RM) 12.0, which is the approximate upstream extent of tidal influence.

Table 44: The Duwamish Estuary habitat changes from 1854 to 1986 (Blomberg et al. 1988)

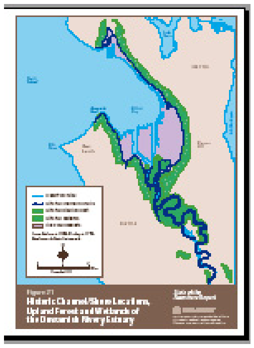
	Year (percent change)				Cumulative Percent Change
Habitat Types	**1854**	**1908**	**1940**	**1986**	
Medium depth water (acres)	440	410 (-7%)	390 (-5%)	360 (-8%)	-18%
Shallows and flats (acres)	1,450	1,080 (-26%)	130 (88%)	25 (-81%)	- 98%
Tidal marshes (acres)	1,170	970 (-17%)	160 (-84%)	20 (-88%)	- 98%
Tidal swamps (acres)	1,230	590 (-52%)	0	0	- 100%
Riparian shoreline (ft)	93,000	90,000 (-3%)	38,000 (-58%)	19,000 (-50%)	- 80%
Development Conditions					
Deep water (acres)	—	240	210 (-12%)		
Developed shorelands and floodplain (acres)	0	1,210	3,750 (+310%)	5,220 (+39%)	+430%
Developed shoreline (ft)	0	4,000	47,000 (+1175%)	53,000 (+12%)	+1,430%
New shoreline from fill (ft)	—	21,000	28,000 (+33%)	28,000	—

Shoreline Conditions

Urban and industrial development over the past century has greatly modified shoreline habitats in the Duwamish Estuary and Elliott Bay. With the exception of the Magnolia Bluff area, virtually 100 percent of the shoreline of the estuary and bay have been modified with various types of armoring including levees and dikes, riprap, bulkheads and seawalls, rubble, or steepened mudbanks. In Elliott Bay, overwater structures are the prominent shoreline modification, occupying over 65 percent of the bay shore. Behind the overwater structures, riprap and seawalls predominate although exposed sand and mud substrates are present as well.

Table 45 summarizes the type and amount of shoreline armoring and modifications present in the Duwamish Estuary and Elliott Bay while Figures 21 to 25 map these modifications. The following sections discuss in greater detail the level and degree of shoreline modifications in the study area. CSO and storm drain discharges, sediment contamination, and dredge and fill operations are also discussed in these sections.

Figure 21 Historic channel/Shore Locations, Upland Forest and Wetlands of the Duwamish River Estuary

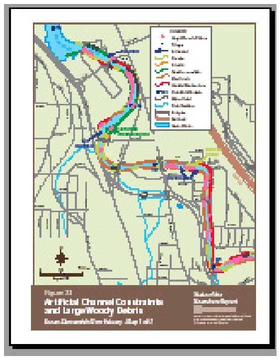


Click here to view figure

Figure 22 Artificial Channel Constraints and Shoreline Modifications – Elliott Bay & Duwamish Waterway

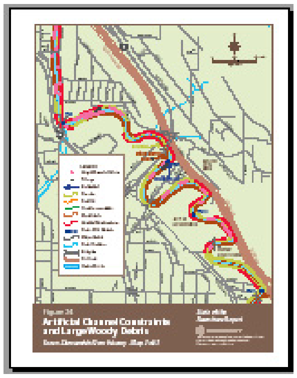
Click here to view figure

Figure 23 Artificial Channel Constraints and Large Woody Debris – Map 1 of 3



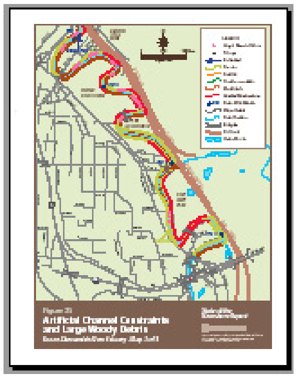
Click here to view figure

Figure 24 Artificial Channel Constraints and Large Woody Debris – Map 2 of 3



Click here to view figure

Figure 25 Artificial Channel Constraints and Large Woody Debris – Map 3 of 3



Click here to view figure

Table 45. Elliott Bay/Duwamish Estuary shoreline habitat and substrate survey results (Port of Seattle, unpublished data).

Duwamish Waterway – River Mile 11.0 to River Mile 5.3			
Habitat/Substrate	**Linear Feet**	**Miles**	**Percentage of Shoreline (both banks)**
Riprap (visible from river)	33,706	6.38	56.0
Bulkhead (near vertical)	1,697	0.32	2.8
Mudbank	29,993	5.68	49.8
Shoal/mudflat (near or below MLLW)	5,342	1.01	8.9
King County levees	13,604	2.58	22.6
Trees*	21,338	4.04	35.4
Shrubs	45,140	8.55	75.0
Grass	3,126	0.59	5.2
LWD (Number per mile)		9.5	
* Includes 33 individual trees each having a 25-ft dripline (total of 850 ft)			
Duwamish Waterway – River Mile 5.3 North to Mouth of Duwamish			
Habitat/Substrate	**Linear Feet**	**Miles**	**Percentage of Shoreline (both banks)**
Riprap (exposed)	40,450	7.66	49.8
Riprap (under dock)	13,000	2.46	16.0
Vertical bulkhead	4,300	0.81	5.3
Exposed sand/mud substrate	45,400	8.60	55.9
Inwater structures (i.e., moorages, extensive piling)	12,300	2.33	15.1
Vegetated shoreline	22,400	4.24	27.6
Rubble shoreline	5,450	1.03	6.7
Overwater structures (i.e., docks and piers)	12,150	2.30	15.3
Elliott Bay – Don Armeni Park to Terminal 91			
Habitat/Substrate	**Linear Feet**	**Miles**	**Percentage of Shoreline (both banks)**
Riprap (exposed)	24,850	4.71	35.7
Riprap (under dock)	34,350	6.51	49.3
Vertical bulkhead/concrete seawalls	11,300	2.14	16.2
Exposed sand/mud substrate	11,750	2.23	16.9

Duwamish Waterway – River Mile 11.0 to River Mile 5.3			
Habitat/Substrate	**Linear Feet**	**Miles**	**Percentage of Shoreline (both banks)**
Inwater structures (i.e., moorages, extensive piling)	10,250	1.94	14.7
Vegetated shoreline	3,150	0.60	4.5
Rubble shoreline	2,800	0.53	4.0
Overwater structures (i.e., docks and piers)	45,800	8.67	65.8

Shoreline Armoring

Types and Distribution

Between the late 1800s and the mid-1900s, the Duwamish Estuary and Elliott Bay underwent massive modifications as the navigation channel and Harbor Island were constructed. The creation of the waterways involved dredging navigational channels, filling shallow habitat such as marshes and flats, and armoring of the shorelines with dikes, levees, bulkheads, and other structures. This development resulted in replacement of about 9.3 mi of meandering river with 5.3 mi of straightened channel. Nearly 100 percent of the shorelines of the estuary downstream of RM 11 are modified by dikes, levees, or revetments. From RM 11 to the Turning Basin (RM 5.3), a 1999 field survey determined that 56 percent of both shorelines had visible riprap armoring and another 3 percent of the shoreline had vertical bulkheads occupying some portion of the intertidal zone (Table 45) (Port of Seattle, Unpublished data). In many areas, this armoring permanently altered the upper intertidal zone, but nearly 60 percent of the shorelines included mudbanks or sandbanks and shoals at lower intertidal elevations (Figures 22 through 25). In the last few years, riprap or revetment repairs needed to protect adjacent properties have included placement of boles with attached rootwads projecting from the bank and plantings of riparian vegetation (i.e., willows) along the upper bank. A relatively small proportion of the shoreline in this area (RM 11 to RM 5.3) is covered by overwater structures, primarily highway and railroad bridges.

Below the Turning Basin, except in areas that have been actively enhanced or restored, the extent of shoreline armoring is significantly greater than that upstream of the basin. From RM 5.3 at the Turning Basin north to RM 0.0 at the southwest corner of Harbor Island, about 65.8 percent of the shoreline is riprapped with another 5.3 percent having near-vertical bulkheads (Figure 22) (Table 45) (Port of Seattle unpublished data). As in the upper reach of the estuary, a substantial portion of the shoreline still has middle to lower intertidal areas that are sand or mudflat. Except where deeper berths have been dredged from the shoreline to the navigation channel, these intertidal sandflats and mudflats are continuous with the shallow subtidal sand and mud shelf adjacent to the navigation channel (Tanner 1991).

Around the shoreline of Elliott Bay, from Pier 91 to near Duwamish Head (Don Armeni Park), nearly 90 percent of the shoreline is riprapped or armored with rubble; and 16.2 percent of the shoreline has vertical bulkheads or seawalls (much of the shoreline is bulkheaded in the upper intertidal zone and riprapped in the lower zone). (Table 45) (Port of Seattle unpublished data). From Pier 91 to West Point, armoring primarily consists of riprap and bulkheads at the top of the beach. Along the Elliott Bay Marina, armoring is continuous; along the residential community of Magnolia Bluff armoring is discontinuous (Figure 22). West of the residential community an unarmored shoreline extends for about 3,870 linear ft along the toe of Magnolia Bluff. The remaining 1,700 linear ft to West Point is a low-angle sand and gravel beach with riprap near the top of West Point. The entire area between Duwamish Head and Alki Point is either riprapped or has a concrete seawall at the top of the beach (Port of Seattle aerial photographs) (Figure 22).

Effects Upon Nearshore Ecosystems

The primary function of revetment construction is the mechanical armoring of natural riverbank and upper beach soils against slumping, sloughing, bank scour, and erosive transport of failed bank materials from the affected site. Revetments, bulkheads, and riprap constitute fill and are often used to retain fill. Levees also are fill and often result in armored banks. They also include raised fills placed above the adjoining floodplain at or near the riverbank in order to contain flood flows within a highly channelized conveyance corridor. The function of levees is both to prevent migration or widening of the river channel, as is the case with revetments, and to prevent flooding of lands within the former floodplain; thus levees not only disconnect off-channel habitat from mainstem rivers, they also dramatically alter the hydrologic regime of former floodplain habitats. Channelization and bank armoring transform formerly heterogeneous banks, composed of a variety of substrates, to steep banks composed of uniform cobble to boulder-sized material. Natural structural features such as exposed tree roots, LWD, and undercut banks are eliminated.

Studies investigating the effects of shoreline armoring in the study area were not identified, but studies conducted in other areas indicate that juvenile salmonid densities and species diversity are generally lower near riprap banks than natural banks (Knudsen and Dilley 1987, Peterson 1999). The abundance of juvenile chinook and coho salmon, and sub-yearling trout, is significantly correlated with the amount of wood cover for both natural and hydromodified banks (Beamer and Henderson 1998, Peterson 1999). Sub-yearling chum preferred aquatic plants and cobble—cover types that were most common in natural banks (Beamer and Henderson 1998)—while yearling and older steelhead trout densities were unaffected or increased at riprap-stabilized banks (Peterson 1999).

In the nearshore environment, shoreline armoring is often placed to reduce shoreline erosion and thereby protect adjacent upland properties. Such armoring deprives adjacent beaches of sediment sources needed to maintain the natural beach slope and substratum. Armoring of the shorelines of Elliott Bay has largely stopped shoreline and bluff erosion and eliminated sediment sources feeding the beaches and sand spits of Duwamish Head and Alki Point. Feeder bluffs along Magnolia Bluff remain partially or completely active, however, and continue to feed sediment to West Point and to the broad sandflats south of West Point. These shallow subtidal sandflats and remnant sandy areas between Alki Point and Duwamish Head support productive eelgrass patches important to a variety of marine resources.

Removal of bank vegetation associated with shoreline armoring also reduces shade, overhanging cover, LWD recruitment, and inputs of terrestrial insects and fine particulate organic matter.

Terrestrial insects and fine particulate organic matter are important components of the food chain in rivers and lower river estuaries (Vannote et al. 1980). In rivers, reduced shade can result in temperatures that equal or exceed the tolerance of salmonid fishes (Sullivan et al. 1990). In estuarine areas, tidal movements and flushing tend to reduce the importance of this function of temperature control. However, on surf smelt spawning beaches, a higher survival of eggs deposited in the intertidal zone has been observed on shaded beaches compared to unshaded beaches (Penttila 2000).

Data Gaps

Despite the level of shoreline armoring in the Duwamish Estuary, Elliott Bay, and other urban embayments adjacent to anadromous streams, the effects of armoring on nearshore ecosystems have not been studied extensively. Table 46 shows the identified data gaps.

Table 46: Data gaps for shoreline armoring

Data Gaps – Shoreline Armoring
▪ There have been no definitive studies investigating the effects of armoring on juvenile salmon feeding opportunities. A few studies have investigated changes in the epibenthic community on armored habitats vs. natural habitats. Armored habitats have been found to provide suitable habitat for some forms of epibenthos that are known prey of juvenile salmonids; however, the ecological significance of different epibenthic communities to salmonids has not been studied.
▪ There have been no quantitative studies investigating the effects of shoreline armoring and associated shoreline steepening on the vulnerability of juvenile salmonids to predation. Existing data are qualitative, observational, or anecdotal (Heiser and Finn Jr. 1970; Pentec 1991).
▪ Long-term multi-estuary studies investigating residence time, survival, and growth in disturbed and undisturbed estuaries are needed to determine how highly modified environments affect salmonid populations.

Overwater Structures

Types and Distribution

Overwater structures, primarily in the form of docks, piers, and marginal wharves, are prevalent in the estuary, particularly in Elliott Bay. From the Turning Basin (RM 5.3) to the mouth of the Duwamish River, overwater structures occupy about 12,150 linear ft or 2.3 mi on both banks of the river (Figure 21). This represents about 15 percent of the lower estuarine shoreline. Along Elliott Bay, from Duwamish Head to Pier 91, overwater structures used primarily for industrial and shipping activities dominate the shore. About 45,800 linear ft or 8.67 mi of shoreline representing about 66 percent of the bay shore is composed of overwater structures (Figure 22) (Table 45) (Port of Seattle, unpublished data). Data for areas northwest of Pier 91 and between Duwamish Head and Alki Point have not been collected, but these areas are essentially free of overwater structures. The exception is the Elliott Bay Marina, located adjacent to Pier 91. Overwater structures in the upper Duwamish Estuary between RM 11.0 and RM 5.3 are limited to road and railway bridges.

Effects Upon Nearshore Ecosystems

Overwater structures affect intertidal and shallow subtidal organisms and habitats by casting shade, as well as by causing changes in wave action, climate, and substrate. These physical changes alter plant communities, such as kelp and eelgrass beds, and change nearshore food webs (Penttila and Doty 1990; Fresh et al. 1995; Thom and Schreffler 1996; Nightingale and Simenstad 2001). Docks and other overwater structures pose potential barriers or inhibitors to juvenile salmon migrating along shallow-water habitats of Puget Sound during their emigration to the Pacific Ocean. Juvenile ocean-type chinook and chum salmon, the two most abundant juveniles in the Duwamish Estuary, are believed to be particularly vulnerable because they migrate along the nearshore in shallow water (Weitkamp 1982; Tanner 1991; Simenstad et al. 1991; (Simenstad et al. 1982). The modification of salmonids' migrating behavior in response to overwater structures may also increase their susceptibility to predation (Simenstad et al. 1982).

Three studies were identified that evaluated the behavior and responses of juvenile salmonids to overwater structures in the Duwamish Estuary and Elliott Bay. Observations by Taylor and Willey (1997) determined that the migration pattern for juvenile chum, chinook, and coho salmon appeared to be from south to north along the Seattle waterfront, which is believed to be the typical Green/Duwamish River migration pattern. Although observations were qualitative, occasional fish were observed migrating in the opposite direction or making no net migration progress, which could have been caused by disorientation from moorage facility structures. Chinook showed a slower migration rate through the facility. No evidence of increased avian predation was observed at the facility. Weitkamp (1982) evaluated the migratory responses of juvenile salmonids in the vicinity of Piers 90 and 91 on Elliott Bay. Juveniles readily moved along and fed under the outer edge of the piers and under a detached portion of one pier. However, they showed a great reluctance to pass into darker areas beneath the wood-supported apron. In another study, Werthamp and Farley (1976) observed juvenile salmon along open shorelines and under piers in the lower Duwamish. They noted that more chinook were seen along shorelines than under piers, but that coho showed little reluctance to enter areas covered by piers and over deeper water. (For additional information, refer to Section 10 – Overwater Structures, in this report).

Data Gaps

Studies conducted directly in Elliott Bay as well as other areas repeatedly verify that changes in the underwater light environment affect salmonid behavior and physiology. Table 47 shows the identified data gaps.

Table 47: Data gaps for overwater structures

Data Gaps – Overwater Structures
▪ Quantitative data are needed to determine the effects of overwater structures on migrating salmonids.
▪ Quantitative data are needed to determine the effects of overwater structures on predator-prey interactions, shifts in species composition, and physical dynamics of nearshore habitat.
▪ Quantitative and experimental data are needed to assess the risk to juvenile salmonids posed by:
▪ Delays in migration caused by disorientation
▪ Loss of schooling in refugia because fish schools disperse under low light conditions
▪ Changes of migratory route into deeper waters without refugia to avoid the light change
▪ Increases in losses to predators attracted to overwater structures.

Dredging

Current and Historical Dredging Sites

From the late 1880s through mid-1900s, extensive dredging in the Duwamish River and Estuary straightened the meandering channels and modified other natural river features that existed prior to the industrial development in the lower basin. As industrial development continued, the Duwamish River and East and West Waterways were deepened and widened to provide vessel access to these industries. Together, the three waterways currently provide over 7 mi of inland navigation accessible from Elliott Bay, Puget Sound, and the Pacific Ocean.

The ACOE is responsible for maintaining these waterways. Most of the dredging projects have taken place in the lower Duwamish Waterway (up to approximately river mile 5), where river sediments accumulate most rapidly. A review of ACOE (Seattle District) records indicates that maintenance dredging began in the late 1920s and has continued, on average, every two to three years. In some years, dredging projects included expanding the East and West Waterway navigation channels. The yearly volumes of sediment dredged from the waterways have varied widely. Since 1931, the total volumes have ranged from approximately 20,000 cubic yards (cy) of sediments to approximately 878,000 cy. Over the last 20 years, maintenance dredging volumes have ranged from about 34,000 cy to 206,000 cy. Additional maintenance dredging in the Upper Duwamish Waterway is proposed beginning in 2001.

Dredging within the East and West Waterways has occurred sporadically, with no routine maintenance dredging in at least the past 30 years (Arden, H., ACOE, per. comm., November 6, 2000). However, in late 1999 and early 2000, the ACOE conducted a channel-deepening project in the East Waterway to allow larger container vessels access to the Port of Seattle's Terminal 18. Approximately 212,000 cy of sediments were dredged from a large section of the East Waterway increasing the channel depth from –43 ft MLLW to a maximum of -51 ft MLLW.

Prior to the 1970s, sediments were typically removed by hydraulic dredge. The excavated sediments were pumped to the surface and usually deposited on the adjacent shoreline. With the implementation of new regulations concerning water quality and dredged material disposal beginning in the mid-1970s, dredging methods switched to the use of the clamshell dredge. This allows the dredged materials to be brought to the surface, loaded onto a barge, and transported to an off-loading site. Under the Puget Sound Sediment Dredged Disposal Analysis (PSDDA) program administered by the ACOE, EPA, WDOE, and DNR, sediment quality standards determine if dredged sediments are suitable for open water disposal or other approved use, or must be disposed of at an approved confined disposal site (i.e., landfill). The PSDDA program established eight open water disposal sites in Puget Sound to accept dredged sediments meeting sediment quality standards. Dredged sediments from the Duwamish that met the sediment quality standards were initially disposed of at the Four-Mile Rock openwater site. This site was subsequently closed and a new open water disposal site was established in central Elliott Bay.

Beginning in 1984, sediments dredged from the Duwamish Waterway have been used as capping material for several nearshore remediation projects in Elliott Bay and in the West Waterway (Sumeri 1996). These projects have used "clean" sandy material to cover and isolate *in-situ* contaminated sediments or have been used in confined aquatic disposal (CAD) projects. The first CAD project in Puget Sound was conducted in 1984. In this project, 1,100 cy of sediments contaminated with PCBs and metals were dredged from the Duwamish Waterway. The contaminated sediments were bottom-dumped into a long pit in the West Waterway and covered by 4,200 cy of clean sand dredged from the Upper Duwamish Waterway. Subsequent monitoring of the cap indicated no diffusion of contaminants into the cap.

Between 1989 and 1994, four contaminated-sediment capping projects were conducted along the Seattle Waterfront. These included the Pier 51 Ferry Terminal Expansion Project Cap, the Denny Way CSO Cap, the Pier 53-55 Sewer Outfall Cap, and the Pier 64/65 Cap. All four sites were identified as priority cleanup sites, although the specific contaminants of concern and contaminant concentrations varied for each site. The material for each capping project, ranging from approximately 10,000 cy (Pier 51) to 22,000 cy (Pier 53-55), came from maintenance dredged material from the Upper Duwamish Waterway.

<u>Effects Upon the Nearshore Ecosystem</u>

State and federal regulations exist to minimize potentially adverse environmental impacts from dredging operations in the Duwamish River and Estuary. Nevertheless, some unavoidable impacts to the nearshore environment (and at offshore disposal sites – not covered in this review) do occur. These impacts are often described as short-term and long-term effects. Short-term effects are those impacts usually associated with the actual dredging operations. These impacts generally include temporary increases in noise levels, temporary changes in water quality, and destruction of non-mobile benthic animals. Long-term effects from dredging include habitat modification such as changes in depth, substrate, and sediment contaminant concentrations. The physical area that may be directly or indirectly affected is dependent on a number of factors, including area dredged, volume and depth, sediment composition and contaminant concentrations, flow and currents, and timing of the work. These factors may be quite variable depending on the specific project.

In general, increased noise levels during dredging can result in temporary avoidance of the work area by fish and wildlife for which the Duwamish Estuary provides important habitat.

Temporary increases in turbidity from sediment resuspension and potential localized reduction in DO can also adversely affect fish and other aquatic species. In addition, dredging in areas with contaminated sediments can result in the resuspension of these contaminants, which may be harmful to aquatic life. However, the volume of sediments resuspended during dredging operations is typically small and the resulting sediment plumes are usually very localized, thus limiting exposure to aquatic organisms. To minimize impacts to salmonids, dredging in the Duwamish, as well as in most nearshore areas, is restricted to those times of the year when migrating juvenile salmonids are least likely to be present. Timing restrictions for reducing impacts to other species do not exist.

While dredging can result in short-term loss of non-mobile benthos and a temporary reduction in abundance and diversity, studies have shown many of these areas become recolonized by infauna and epifauna (McCauley et al. 1977, Richardson et al. 1977, Romberg et al. 1995, Wilson and Romberg 1995). Diversity and health of the benthic assemblage recolonizing these dredged areas may be able to recover and be similar to those of the benthic community that existed previously depending on depth, substrate and other factors.

Data Gaps

Records of ACOE dredging in the Duwamish begin in 1928. No records of earlier dredging activities in the Duwamish were found.

Little is known about the cumulative effects of dredging on the nearshore ecosystem. Additional studies are needed to determine the short-term and long-term impacts to multiple species and ecosystem functions at dredging and disposal sites.

Filling

Current and Historical Filling Sites

The Elliott Bay and Duwamish shorelines have experienced substantial modification since the mid to late 1800s. Most of the intertidal habitat of the eastern shoreline of Elliott Bay was filled and the shoreline bulkheaded to create the present Seattle Waterfront. Much of the Duwamish shoreline was similarly modified, as dredged material from the river was used to fill large portions of the mudflats and shorelines were hardened. These filled areas created and expanded upland areas for industrial development.

Effects Upon the Nearshore Ecosystem

The filling of intertidal areas and loss of intertidal habitat in Elliott Bay and the Duwamish has had perhaps the greatest single impact on the nearshore ecosystem. Most of the intertidal habitat functions are discussed elsewhere in this document (see Section 10 – Filling).

Data Gaps

The extensive filling of the Lower Duwamish River and Elliott Bay has undoubtedly had a dramatic impact on ecosystem processes, structure, and functions. Yet, there have been few studies that have attempted to quantify lost functions and the resultant impacts on aquatic resources.

Sewage Discharges

Types and Distribution

Prior to 1987, the entire treated effluent from the Renton Sewage Treatment Plant flowed into the Duwamish Estuary between RM 6 and RM 7, after which it was diverted to an outfall off Duwamish Head. Prior to diversion, discharges from the Renton plant affected water quality in the estuary by depressing DO levels and increasing levels of nutrients and ammonia beyond U.S. EPA guidelines. Diversion of the Renton outfall to a new deepwater diffuser in 1987 produced marked improvements in water quality in the estuary. These improvements are shown in increases in the minimum DO and in the annual average ammonium concentration in the estuary (Figures 26 and 27). Improvements have also been observed in levels of total phosphorus, total nitrogen, and residual chlorine (Metro 1989). The present location of the outfall is in deep water off Duwamish Head, outside of the study area.

Another outfall, discharging treated effluents from the West Point Sewage Treatment Plant, is located in deep water at the northern boundary of Elliott Bay. This outfall is also outside of the nearshore study area.

Figure 27 Tanner (1991) identified 55 CSOs and storm drains operated by the City of Seattle and Metro discharging treated and untreated effluents and stormwater runoff into the Duwamish Estuary and Elliott Bay. CSOs discharge organic and inorganic substances from untreated sewage during stormwater overflows, although about 90 percent of discharges consist of stormwater. Similar constituents discharge from urban stormwater sources. Thirty-five CSOs and storm drains discharge to the shore of Elliott Bay and the East and West Waterways, and 20 discharge to the Duwamish Estuary, upstream of Harbor Island (Tanner 1991). Annual discharges of 1.6 billion gallons (1995) occur through the County's CSO system. This discharge level is down from nearly 2.4 billion gallons per year during the period between 1981 and 1988 (Parametrix and King County Department of Natural Resources 1999). Discharges from the City CSO system are currently being quantified.

Effects Upon Nearshore Ecosystems

Parametrix and King County (Parametrix and King County Department of Natural Resources 1999) presents a comprehensive and current discussion of CSOs and storm drains in the Duwamish Estuary, and this section relies heavily on their work. Stuart and Cardwell (1987) found 7 metals and 20 organic chemicals or chemical groups, including 12 polycyclic aromatic hydrocarbons (PAHs), 5 phthalates, and 3 volatile organic compounds in samples collected from CSOs. Parametrix and King County Department of Natural Resources (1999b) found 7 metals and 16 organic compounds in CSOs that were considered constituents of potential concern. WDOE identified 25 areas in the estuary and bay that have concentrations of substances in sediment that exceed State sediment quality standards. Many of these sites received these contaminants via storm drains and CSOs.

Studies conducted below CSOs have found that most substances settle and adsorb to the sediments at varying distances from the CSO, depending upon velocity and flow through the pipe, particle size, and surrounding receiving water conditions. The areas of deposition around Elliott Bay and Duwamish CSOs have ranged from 1,000 to 5,000 square meters (Parametrix and King County Department of Natural Resources 1999a,b). Preliminary information suggests that the observed deposition around these CSOs is primarily historical and no longer occurs. Further studies are underway to investigate this hypothesis (K. Huber, pers. comm.). The effects of sediment contamination on the nearshore environment are discussed more fully in the Sediment Contamination section.

CSO discharges can affect habitats in the Duwamish Estuary and Elliott Bay in other ways besides the discharge of contaminants. Increases in discharges from CSOs and storm drains that occur during the wet season can result in erosion and sedimentation. Parametrix and King County Department of Natural Resources (1999b) found potential risks to the benthic community in localized areas from sedimentation and scouring. Sedimentation and scouring risks occurred over less than 1 percent of the study area.

Resuspension of chemically contaminated sediments during erosion (scouring) can result in the re-release of potentially toxic chemicals into the water column. Freshwater runoff and CSO discharges can lower the salinity of receiving waters. CSOs also have the potential to affect DO concentrations and pH if their effluents are high in nutrients and organic materials. Additionally, CSO and stormwater discharges from summer rainstorms may be warmer or colder than receiving waters, raising or lowering the ambient temperature.

Lastly, CSOs are the primary source of untreated domestic wastewaters in the Duwamish River, and Elliott bay, releasing potentially harmful microbial pathogens. In microbial surveys conducted by Heyward et al. (1977), fecal coliform levels were found to be 77 times higher in butter clams near CSOs than in water on King County beaches near King County's wastewater treatment plants. Although CSOs contribute to bacterial discharges, there are many sources of bacteria in the nearshore study area and high shellfish levels persist even in low water months. Harvesting of shellfish has been prohibited in Elliott Bay and the eastern shore of the Main Basin of Puget Sound because of the potential for bacterial discharges (Stober and Pierson 1984).

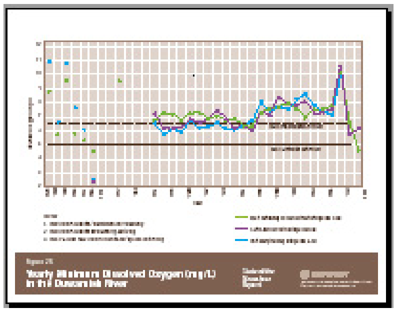
Data Gaps

Although numerous sediment and water quality investigations have been conducted in the Duwamish Estuary, some data gaps remain. Table 48 shows the identified data gaps.

Table 48: Data gaps for sewage discharges

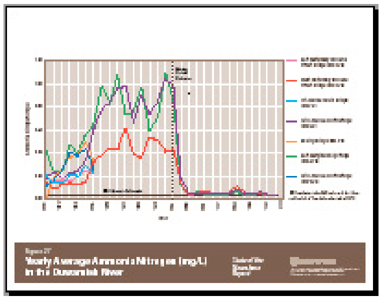
Data Gaps – Sewage Discharges
▪ There is a lack of water and sediment monitoring data for nearshore habitats—most studies are conducted in deeper water, farther offshore. ▪ The CSO Water Quality Assessment conducted by Parametrix and King County DNR uses a water quality assessment model that could be further refined and validated by implementing a sampling program to verify the model's prediction of sediment transport and chemical concentrations. ▪ Additional studies are needed to determine the contaminant levels and impacts of acute stormwater discharges in the Duwamish and other industrialized drainages

Figure 26 Yearly Minimum Dissolved Oxygen (mg/L) in the Duwamish River



Click here to view figure

Figure 27 Yearly Average Ammonia Nitrogen (mg/L) in the Duwamish River



Click here to view figure

Sediment Contamination

Types and Distribution

Numerous studies investigated sediment contamination in the Duwamish Estuary and Elliott Bay (Tetra Tech 1988; Weston 1993, 1998, 1999; EVS and Weston 1996; Aura Nova and WDOE 1995). Studies indicate that PCBs, PAHs, metals, other organic compounds (i.e., phthalate esters and chlorinated benzenes), pesticides, and TBT are present in river and bay sediments at concentrations that are above state sediment quality standards (SQS; WAC 173-204). PCBs and bis(2-ethylhexyl)phthalate (BEP) appear to be the most widespread contaminants of potential concern, followed by metals (primarily mercury, cadmium, and zinc) and PAHs. Contaminants have entered the river and bay via several transport pathways or mechanisms, including spillage during product shipping and handling, direct disposal or discharge, contaminated groundwater discharge, surface water runoff, stormwater and CSO discharge, or contaminated soil erosion (Weston 1999).

Weston (1999) evaluated sediment chemistry at about 300 surface sediment stations and 17 subsurface stations within the Duwamish Estuary from RM 7.1 to RM 0.9. Weston (1993 and 1998), EVS and Weston (1996), and Aura Nova and WDOE (1995) evaluated sediment chemistry at approximately 350 surface sediment stations and 60 subsurface stations within southern Elliott Bay, the East and West Waterways, and along the waterfront. Sediment concentrations were compared to state screening guidelines typically used to determine whether remediation is required in a specific area (Cleanup Screening Levels [CSL]).

In the Duwamish Estuary, several organic compounds and metals were observed at elevated concentrations throughout the estuary, but concentrations exceeding CSL standards were observed in fewer than 10 percent of surface sediment stations. The most prevalent contaminant found at elevated concentrations was BEP. This substance exceeded CSL screening guidelines at 16 stations within the estuary. PCBs were the next most prevalent substance, exceeding screening guidelines at 12 stations; they were followed by TBT, (7 stations), mercury (5 stations), and several PAHs (1 to 3 stations). Arsenic, lead, and zinc each exceeded screening guidelines at 1 station. The highest number of exceedances was distributed in the general vicinity of the Turning Basin (RM 5.3) (Weston 1999).

In subsurface sediment, elevated concentrations were observed at fewer total stations, but only 17 subsurface sediment cores were collected. PCBs and mercury were observed at concentrations exceeding screening guidelines at 5 and 4 stations respectively, followed by BEP (2 stations), and lead, arsenic, and zinc (1 station each). These data indicate that nearly 40 percent of the subsurface sediment samples collected in the estuary had concentrations of substances that exceeded state screening guidelines (Weston 1999).

In Elliott Bay, cadmium and mercury were observed in surface sediments at concentrations exceeding CSL screening guidelines in greater than 50 percent of samples collected in the East and West Waterways and the north shore of Harbor Island, a designated Superfund site. PCBs and several PAHs were the most prevalent organic compounds observed in this portion of Elliott Bay. TBT was also observed at elevated concentrations around Harbor Island. For these organic compounds, concentrations above those found in Carr Inlet reference samples were widespread with the occasional exceedance of CSL screening guidelines (Weston 1993; EVS and Weston 1996). Immediately west of Harbor Island, in the upper bay nearshore, is an extensive area of PAH contamination associated with a former wood treatment facility, another Superfund site. Weston (1998) estimated that approximately 50 acres of nearshore sediment in this area is contaminated with PAHs at concentrations exceeding CSL screening guidelines. PCBs were also observed to exceed screening guidelines in this area, but were not as widespread as the PAHs. Along the Elliott Bay waterfront, studies have identified mercury, silver, lead, zinc, and PAHs at concentrations exceeding CSL screening guidelines (Aura Nova and WDOE 1995). Mercury exceeded its respective CSL throughout the waterfront area between Piers 46 and 63, except in areas that have been capped (Piers 51 and 53 to 55). The remaining metals and PAHs exceed their respective CSL screening guidelines sporadically, often between piers and slips.

In summary, the highest concentrations of sediment contamination were found near the two Superfund sites at Harbor Island and immediately to the west. These areas were highly contaminated with metals, particularly mercury and cadmium, PAHs, and PCBs. Mercury is prevalent along the Elliott Bay waterfront, with other substances occasionally exceeding screening guidelines next to piers. Lower concentrations of contaminants were observed in the Duwamish Estuary, with fewer than 10 percent of samples having concentrations exceeding screening guidelines. A higher proportion of elevated concentrations was observed at depth, but the level of characterization in the subsurface is considerably lower than in the surface sediments.

Effects upon the Nearshore

The CSL screening guidelines are concentrations that are associated with minor adverse effects to biological resources (Weston 1999). Hence, the sediment data suggest that biological effects to aquatic organisms may occur in some areas of the bay and estuary. Toxicity tests have found that the sediments from the more industrialized areas of the Duwamish Estuary are toxic to benthic dwelling organisms and studies have found significant alterations in the benthic community (Armstrong et al. 1981; PTI and Tetra Tech 1988).

PCB bioaccumulation in juvenile chinook salmon collected in the estuary has been found to be associated with impaired growth and increased mortality after disease challenge (Varanasi et al. 1993; Arkoosh et al. 1998). McCain et al. (1990) and Varanasi et al. (1992) found that concentrations of PCBs in juvenile chinook salmon collected in the Duwamish Waterway are higher than levels found in juvenile salmon collected in non-urban areas. Stein et al. (1995) found that the mean concentration of fluorescent aromatic compounds in bile and hepatic cytochrome P4501A, both biochemical indicators of contaminant exposure, were significantly higher in juvenile chinook salmon collected in the Duwamish Estuary compared to those collected in an non-urban estuary.

Johnson et al. (1994) have demonstrated that elevated concentrations of PAHs and PCBs occur in bile as metabolites of demersal fish species from the Duwamish Estuary. This study also found an increased incidence of reproductive impairment from English sole collected from urban areas. Several studies found that the highest prevalence of liver tumors in English sole were collected in the Duwamish River (Malins et al. 1984, 1985; Krahn et al. 1987; Meyers et al. 1987, 1992, 1994).

A few studies have been conducted on the uptake of chemical contaminants by the aquatic birds and marine mammals that occur in the Duwamish Estuary and Elliott Bay (Riley et al. 1983; Speich et al. 1992; Calambokidis 1985, 1991). Studies have found that PCBs and DDT are accumulated in eggs of blue heron, glaucous-winged gulls, and pigeon guillemots from the Seattle area. While the residues in eggs are thought to be high enough to cause eggshell thinning, they are not high enough to cause reproductive impairment (Speich et al. 1992).

Data Gaps

Numerous sediment investigations have been conducted in the Duwamish Estuary and Elliott Bay; the areal distribution of surficial sediment contamination in the nearshore study area is relatively well known. Table 49 shows several data gaps that have been identified.

Table 49: Data gaps for sediment contamination

Data Gaps – Sediment Contamination
▪ Sediment contamination farther out into Elliott Bay is not as well characterized as in the nearshore. Although juvenile salmonids are less likely to contact these deeper sediments, studies have shown physiological impacts to flatfish associated with highly contaminated areas.
▪ The rate and role of natural attenuation is not well understood in the estuary and bay. Given recent reductions in contaminant inputs, it is not clear whether, or to what degree, natural burial and attenuation is reducing contaminant concentrations over time.
▪ Sediment contamination in the subsurface is not as well characterized as in surface sediments. Understanding the degree of subsurface contamination and the potential for it to become biologically unavailable is important when evaluating dredging and natural attenuation remedial options.
▪ The relationship between observed sublethal biological effects and the survival of fish, such as juvenile salmon and demersal resident marine fish, is largely unknown. Biochemical effects and physiological effects have been associated with contaminated areas, but whether this reduces growth or survival or affects behavior is not clear. As evidence, despite the documented levels of contamination along the Duwamish Estuary, hatchery chinook salmon released to the Green River by the Washington Department of Fish and Wildlife (WDFW) have a high fry-to-adult survival rate compared to other hatchery stocks released to cleaner areas of Puget Sound.

Key Findings

Shoreline Armoring

- Nearly 100 percent of the shoreline of the Duwamish Estuary is modified by riprap, steep mud banks, levees, or bulkheads.
- Seawalls with riprap toes, in conjunction with overwater structures, are present along much of the Elliott Bay waterfront. Seawalls are also present along about half of the sandy beach habitats along Alki Beach.
- The most substantial unarmored area in the study area is about 3,870 linear ft situated along Magnolia Bluff adjacent to Discovery Park.

- Very few studies have evaluated the effects of armoring on fish and other aquatic resources in the study area.

Overwater Structures

- Overwater structures occupy about 66 percent of the Elliott Bay nearshore (8.7 mi) and about 15 percent of the lower Duwamish Estuary (2.3 mi) below the Turning Basin (RM 5.3). Very few overwater structures are present in the upper estuary or areas outside of the waterfront.
- Juvenile ocean-type chinook and chum salmon are believed to be vulnerable to overwater structures, because they migrate along the nearshore in shallow water. Studies have shown that juvenile chinook show reluctance to pass into darker areas under piers. Other studies have shown that chinook, chum, and coho salmon successfully migrate through fish openings under piers.
- Overall, there is a lack of quantitative data to indicate that behavioral responses to overwater structures truly decrease survival of emigrating juvenile salmonids. Quantitative and experimental data are needed to assess the risk posed by these structures.

Dredging

- From the late-1800s through mid-1900s, extensive dredging in the Duwamish River and Estuary straightened the meandering channels and modified other natural river features that existed prior to the industrial development of the basin.
- Maintenance dredging occurs, on average, every two to three years since the late 1920s. Yearly volumes of dredged sediments vary widely ranging from 20,000 cy to approximately 878,000 cy. Over the past 20 years dredging volumes have ranged from 34,000 to 206,000 cy.
- Prior to the 1970s, sediments were typically removed by hydraulic dredge, but after the mid-1970s, dredging methods switched to clamshell dredge, allowing sediments to be loaded and transported to disposal sites.
- Dredging can result in short-term and long-term impacts to habitats and species in nearshore environments

Filling

- Early in the century, most of the intertidal habitat of the eastern shoreline of Elliott Bay was filled and the shoreline bulkheaded to create the present Seattle Waterfront, Duwamish shoreline, and Harbor Island. Historical intertidal filling has likely had the greatest single impact on the nearshore ecosystem in the study area.

Sewage Discharges

- Fifty-five CSOs and storm drains discharge treated and untreated effluents and stormwater runoff into the Duwamish Estuary and Elliott Bay, although mean annual discharges have decreased from 2.4 billion gallons per year (1981-1988) to a current 1.6 billion gallons per year.

- Seven metals and 16 organic compounds have been identified as constituents of potential concern from CSO discharges.
- WDOE identified 25 areas in the estuary and bay that have concentrations of substances in sediment that exceed State sediment quality standards. Many of these sites received these contaminants via storm drains and CSOs.
- Contaminant concentrations in sediment, organic enrichment, and localized areas of sedimentation and scouring pose a risk to organisms in the nearshore bay and estuary.
- Prior to 1987, treated effluent from the Renton Sewage Treatment Plant flowed into the Duwamish Estuary, affecting water quality by depressing DO and increasing levels of nutrients and ammonia beyond U.S. EPA guidelines. After 1987, effluents were diverted to a deepwater outfall outside of the study area. Marked improvements in DO and ammonium concentrations were observed after the diversion.

Sediment Contamination

- Numerous sediment investigations in the Duwamish Estuary and Elliott Bay have found that several organic compounds (i.e., BEP, PCBs, PAHs) and metals (i.e., mercury, cadmium, zinc) are found in sediments at concentrations exceeding state sediment quality standards.
- The most highly contaminated areas are within the East and West Waterways and immediately west of Harbor Island, both associated with Superfund sites. Exceedance of sediment quality standards has also been observed near the Turning Basin (RM 5.3) and along the Elliott Bay waterfront.
- Several studies have found bioaccumulation of chemicals in fish, shellfish, birds and mammals collected in the estuary. Reproductive impairment in English sole and indications of genetic damage in juvenile salmon have been observed. However, the relationship between observed sublethal effects and the survival of fish populations is largely unknown.

Sediment Dynamics and Patterns

Duwamish River

Sediment dynamics of the Duwamish Waterway have dramatically changed since the diversion of the White, Black and Cedar Rivers (by 1916), completion of the Tacoma Water Diversion (1913), and the inception of the Howard Hansen Dam (1962). The completion of these projects has permanently altered peak flows of the Duwamish River by 70 percent (ACOE 1997) and reduced the sediment load at the mouth of the system by at least 75 percent of the Duwamish River's historical sediment load (Dunne and Dietrich 1978; Perkins 1993). By 1917, the channel length of the Duwamish River was reduced by approximately 4 river miles from extensive channel straightening (Blomberg et al. 1988). The lower 6.1 mi of the Duwamish Waterway has undergone regular dredging operations beginning as early as the 1930's for the purposes of navigation (ACOE 1932). This section addresses changes in sediment dynamics that have resulted from altering peak flows, reducing sediment loads, simplifying the channel, and maintaining dredging operations, based on available literature. The mechanisms of sediment transport are discussed below in order to clarify the implications of human alterations to the Duwamish River.

Mechanisms of Sediment Transport

The features of a river are the result of erosional and depositional processes that operate locally to produce scour and fill (over a decadal timescale), and more generally to define long-term channel evolution (over centuries or millennia). While local processes are of immediate concern to river managers, long-term channel evolution has become increasingly relevant in addressing habitat restoration and long-term river management. Sustainable river management and viable channel design require an understanding of the supply, transport, and storage of sediment (Brooks and Shields 1996).

The "sediment system" of a river is a continuum of sediment supply, transport, and storage operating at a range of scales in space and time (Sear et al. 1995). In general, channel reaches can be classified at the watershed scale as source, transport, and response reaches (Montgomery and Buffington 1993). Source reaches occur in the mountainous upper watershed where channel gradients are steep (typically over 20 percent in the Pacific Northwest) and serve as a conduit for sediment supplied from hillslope failures. Transport reaches possess gradients between 3 and 20 percent and are highly dynamic as the result of actively reworking sediments originating from the upper watershed. Transport reaches possess a degree of sediment storage, but at shorter time scales than that of response reaches. For example, gravel bars in a transport reach may vary in age from 1 to 26 years for active bars and 100 years for inactive bars; the main channel that the stream occupies may only be around 50 years old. The ages of these surfaces provides a context for how the stream deposits sediment and reworks the sediment in future years. In contrast, response reaches (< 3 percent gradients) are the lowland portions of rivers that provide relatively long-term sediment storage in the channel network; as an example, floodplain material may be as old as 4,000 years (Brooks and Shields 1996).

Though stream gradient is a factor in sediment transport and storage (as previously described), the residence time of sediments in stream reaches also varies depending on five factors (Brooks and Shields 1996):

- The size of the sediment particles;
- The degree of storage available at a given site (storage sites that are "over-filled" can become sites for sediment supply);
- Whether sediments are in active storage (such as dunes where particles are concentrated but in motion) or in passive storage (where sediments are immobile);
- The influence of vegetation (either from root strength or from large woody debris); and
- Distance from the active channel.

The fate of sediment in channels depends on the quantity and sizes of sediment introduced to the stream channel, their mechanical and chemical durability, the sediment transport capacity and competence of the stream, and the opportunities for deposition along a river. The quantity and sizes of sediment introduced to streams are dictated by sediment supplied from the upper watershed (i.e., landslide activity) and from sediment storage features (i.e., terraces, floodplain, and bars). The sediment transport capacity of a stream is defined as the quantity of a particular grain size that the stream can transport past a cross section in a unit of time (i.e., tons per second per year). The competence of a stream refers to the maximum size of mobile sediment grains (Reid and Dunne 1996).

Sediment transport varies locally depending on the flow velocity across the channel cross-section, and more generally with the volume of flow. The factors that enter into sediment dynamics change over the course of a single flood event and progressively change over time if the characteristics of sediment vary. Sediment storage elements can vary naturally over time with episodic periods of relatively high sediment yield and dynamic channel change (Passmore et al. 1993) that may vary spatially within the channel network (Brooks and Shields 1996).

In addition, sediment storage within the channel network may be enhanced or reduced depending on river management practices. Artificial revetment of channel boundaries often increases the residence time of sediments stored in floodplains and effectively reduces the sediment supplied to the channel; in turn, this can cause erosion of other sources within the river.

Historical Sediment Dynamics of the Duwamish River

Reconstructing the sediment dynamics of the Duwamish River should take into account the processes that influence sediment supply, transport, and deposition. Likewise, sediment transport is also affected by anthropogenic changes in hydrology, sediment loading, and channel form. Included in this section is a discussion of the changes to these variables and the net effect these changes appear to have on sediment dynamics in the Duwamish River.

Alterations in Stream Form and Discharge

Prior to 1900, the Cedar, Black, Green, and White Rivers (including the drainage areas of Lake Sammamish and Lake Washington) drained into the Duwamish River, with an undeveloped drainage area totaling approximately 1,640 square miles. As the result of diverting the White River (1911) and diverting the Black and Cedar Rivers (1916), the Duwamish River drainage was reduced to 483 square miles, a reduction of 70 percent from historical conditions. Over 50 percent of the water volume draining to the Duwamish River was lost when King County and the ACOE agreed to permanently divert the White River into the Puyallup River. The mean annual flow for the Duwamish River was estimated at 2,500 to 9,000 cfs prior to the diversion (Fuerstenberg et al. 1996). By 1996, the mean annual flow of the Duwamish River was estimated to be approximately 1,700 cfs (ACOE 1997), a total reduction between 32 percent to 81 percent.

The Black River received flows from Lake Washington and the Cedar River before converging with the Duwamish River. The discharge of the Black River was reduced by two events: first, by the diversion of the Cedar River to Lake Washington in 1912, and secondly by the construction of the Hiram Chittenden Locks in 1916, which lowered Lake Washington by 9 ft. The loss of flows from Lake Washington and the Cedar River diminished the Black River to a small creek, and further decreased flows draining to the Duwamish River (ACOE 1997).

By 1913, the City of Tacoma completed a water diversion dam on the Green River, with a maximum withdrawal of 113 cfs. In 1962, the Howard Hansen Dam (HHD) was built by the ACOE in the Eagle Gorge of the upper Green River. Located upstream from the Tacoma

Diversion Dam, the Howard Hansen Dam was authorized for flood control and low flow augmentation. Authorized operation of the dam limits flows to a maximum of 12,000 cfs, resulting in dramatically reduced flooding in the historical Duwamish River floodplain (ACOE 1997; Fuerstenburg et al. 1996).

Management of Howard Hansen Dam directly affects peak and low flows found in the Duwamish Waterway, given that more than 90 percent of the Duwamish basin is currently drained by the Green River (Dexter et al. 1981). During the winter, the reservoir behind HHD is kept nearly empty and the river flows through a gate-controlled outlet tunnel. The HHD impounds flows exceeding 12,000 cfs and later releases them at a rate that protects channel capacity downstream and minimizes damage to levees on the Green River. This cycle of holding and releasing is repeated as often as necessary. By late February, the likelihood of flooding greatly diminishes as the dam impounds water for conservation purposes. Usually refill operations begin in mid-April for summer and early fall low-flow augmentation (S. Madsen, pers. comm.). Historically large flood events on the Duwamish River were generally the result of warm rainfall melting an already existing snow pack during the months from October to March. The highest flows generally occurred in December or January, declining through March followed by a snow melt peak in April or May (ACOE 1997). Dam operations clearly change the seasonal hydrograph of flooding in the Duwamish River by eliminating the highest peaks during the winter and preventing snow melt-related flooding in the spring.

Consequently, flows in the Duwamish River have been permanently altered in the following ways:

- Glacial and snow melt originating from the White and Cedar Rivers no longer augments late summer and early fall low-flows. Low flow augmentation in the Duwamish River appears to rely exclusively on the management of the Howard Hansen Dam.
- Winter peak flows in the Duwamish River have been reduced to 30 percent of their historical volumes as the result of diverting the White, Black, and Cedar Rivers and from Howard Hansen Dam management strategies (GeoSea Consulting 1994; ACOE 1997). Consequently, peak flows in the Duwamish River appear to be limited in their capacity to initiate channel changes such as lateral migration of channel meanders, slough formation, and side channel formation.
- Flooding in the spring is limited to snow melt originating from the Green River drainage, which is further limited by controlled releases from the Howard Hansen Dam. Inhibiting spring floods appears to limit initiation of channel changes and provision of access to off-channel anadromous fish habitat.

In historical times, large floods were mostly responsible for creating side channels, sloughs, LWD deposits, and deltas, and reworking sediment deposits, which benefited fish and wildlife (ACOE 1997). Diversion of the White, Black, and Cedar Rivers, in addition to regulating flows on the Green River, all but eliminated the large floods capable of initiating large-scale channel changes that create and maintain anadromous fish habitat in the Duwamish River and estuary. However, the morphologic consequences of limiting winter and spring peak flows cannot be addressed without also investigating the physical manipulation of the Duwamish River's channel form.

Today, approximately 98 percent of the Duwamish estuary has been filled and converted to industrial and urban uses (ACOE 1997). The Duwamish Waterway was extensively straightened by 1917 (Blomberg et al. 1988) and has been stabilized along most of its length. The ACOE maintains a navigable channel by dredging the length of the Duwamish River from its mouth to the Turning Basin, located at approximately River Mile 6.1 (Stoner 1972). According to studies initiated by Blomberg et al. (1988), 21,000 ft (approximately 4 mi) of shoreline was lost in the Duwamish River due to straightening the channel. The combined loss of peak flows and physical alterations to the Duwamish River prohibits the dynamic interaction between flood flows and sediment deposition in what was once the Duwamish delta. Channelization and bank stabilization simplified the plan form of the Duwamish River by decreasing its sinuosity, eliminating historical meanders, and disconnecting the floodplain from the stream channel.

Regular dredging operations (every 2-3 years) in the Duwamish Waterway has deepened the main active channel for navigation purposes. A report issued by ACOE (1997 p.36) implied that due to dredging practices, the tide migrates farther upstream than it had prior to channelization and dredging. This assumption appears to be valid when considering the combined effects of deepening the channel, reducing the watershed area by 70 percent, and reducing the freshwater discharge by 70 percent (ACOE 1997). Reducing the mean annual flow from 2,500 cfs (conservatively) to 1,700 cfs compromises the stream flow's ability to resist upstream migration of the tide for greater time periods than historically. Dredging the channel lowers the elevation of the channel bottom thereby making it more accessible to a wider range of tides. Tidal activity is reported to dominate sediment deposition in the Duwamish Waterway (GeoSea Consulting 1994) and as a result it may also control the kinds of sediment that are deposited. If tidal activity is occurring farther upstream than it previously had, then it could have changed the composition of the streambed.

Alterations to Sediment Loading

Sediment loading in the Duwamish Waterway continues to consist primarily of silts and clays (or fine sediment), and sands. Larger particles, such as gravels and cobbles, are deposited in the upper portions of the Duwamish drainage in reaches with steeper gradients. Hence, discussion on sediment loading in the Duwamish River is primarily concerned with changes in sand, silt, and clay sediment loading.

The White River originates from the glaciers on Mt. Rainier and, as a result of its origins, contains a substantial fine sediment load. Prior to its diversion to the Puyallup River system, the White River contributed the majority of sediment supplied to the Duwamish River system. The diversion of the White River removed the major source of sediments from the Duwamish floodplain riparian areas, wetlands, and estuary. Dunne and Deitrich (1978) estimated that approximately 75 percent of the total sediment load of the Duwamish River basin originated from the White River. The Cedar River also contributed an undocumented volume of fine sediments to the Duwamish Waterway before its diversion in 1916.

The Howard Hansen Dam may or may not affect sediment loading of fine material and sand to the Duwamish River. Perkins (1993) asserts that the Howard Hansen Dam cut off sediment from 55 percent of the remaining Duwamish watershed, which is an area that was the source of most of the sediment transported by the Green River. The dam is purported to allow fine material (silts and clays) to pass through the gate-controlled outlet, in part as an effort to prevent some degree of sedimentation behind the dam (S. Madsen, pers. comm.). It is further postulated that sediment loading of fine material is similar to or less than pre-dam conditions (S. Madsen, pers. comm.). Whether or not the Howard Hansen Dam influences sand loading is presently unknown and requires more detailed study.

Present Sediment Dynamics of the Duwamish River

Sediment dynamics in a tidally influenced estuary involve more complex interactions than that of an entirely freshwater system. For instance, tidal activity in the Duwamish River re-transports and deposits riverine sediments as far upstream as RM 10 during summer low flows and high tides (ACOE 1997). It is possible that tidal activity plays a larger role in sediment dynamics than in previous times, subsequent to dramatic changes in upper watershed sediment loading, channel straightening, bank stabilization, and on-going dredging operations.

Tides and Salinity

The gravitational forces exerted by the sun and moon dictate the influence of tides by creating fluctuations that vary over daily and monthly time periods. The tides in the Duwamish River estuary are semidiurnal, with marked inequalities in the successive high- or low-water stages. This diurnal inequality necessitates the designation of a higher high water, a higher low water, a lower high water, and a lower low water during each complete tidal cycle of about 25 hours. The datum plane for tide height in the Duwamish River estuary is mean lower low water at a tide reference station about 1 mile northeast of the estuary mouth. Mean lower low water is the average of the lower low water levels (Stoner 1972). According to the ACOE, the mean tide stage is 6.5 ft above MLLW, and maximum and minimum estimated stages are 15.00 ft ± 0.5 ft above MLLW and 4.5 ft ± 0.5 ft below MLLW, respectively.

Circulation of water within a stratified estuary comprises a net upstream movement of water within a lowermost salt-water wedge and a net downstream movement of fresher water in the layer overriding the wedge (Pritchard 1955). The saline wedge water, which has its source in Elliott Bay, oscillates upstream and downstream with the tide. During periods of low fresh-water inflow and high tide stage the salt-wedge has extended as far upstream as the Foster Bridge, 10.2 mi above the mouth. At fresh-water inflow greater than 1,000 cfs the saltwater wedge does not extend upstream beyond the East Marginal Way Bridge (RM 7.8) regardless of the tide height (Stoner 1967). The Duwamish River transports fine material in a freshwater plume emptying into Elliott Bay. Sediments return from Elliott Bay to the Duwamish as a near-bottom sediment load contained in the salt wedge (GeoSea Consulting 1994).

The Duwamish Waterway appears to undergo continual “tidal pumping” of mud in the landward direction (GeoSea Consulting 1994). GeoSea Consulting (1994) explains that flood tide-directed sedimentation of mud is the result of asymmetric tidal currents where the flood tide is faster flowing and of shorter duration than the ebb. Fine sediments are carried in suspension in the flood tide with deposition occurring at high slack water. Given the cohesive nature of mud, the weaker ebb regime appears unable to re-suspend and return the sediments as easily as the stronger flood currents. In contrast, sand is non-cohesive and, despite a weaker ebb current, can be returned towards the sea. Because the duration of the ebb is longer than the flood tide, the net effect would be to transport sand, if present, down-river and out into Elliott Bay (GeoSea Consulting 1994).

GeoSea Consulting (1994) asserts that tidal fluctuations redistribute sediments in Elliott Bay and the Duwamish Waterway as far upstream as the Turning Basin (RM 5.3). They further assert that the flood tide dominates deposition in the Waterway rather than the river itself and that sediments deposited during tidal activity are a mixture of riverine and Elliott Bay sediments. Though some deposition must originate from riverine processes, deposition of silt and clay appear to be more strongly linked to the flood tide-dominated system (GeoSea Consulting 1994).

In their study, GeoSea Consulting (1994) collected data to ascertain net sediment transport patterns in Elliott Bay and the Duwamish River, using a technique known as Sediment Trend Analysis. This approach examines the trends observed in changes to grain-size distributions of existing sediments. A grid of samples is required in order to interpret pathways of sediment transport. Sediment pathways provide patterns of sediment transport and are reported to be an integration of all processes responsible for the erosion, transport, and deposition of sediments over the time period required to form the deposits (GeoSea Consulting 1994). Though GeoSea Consulting comprehensively samples Elliott Bay, sediment samples for the Duwamish River are limited to a single line of sediments. Though their results indicate that upriver transport of Elliott Bay/Duwamish River sediments occur as far as the Turning Basin, the lack of sediment samples is reason for viewing their results with caution.

Sediment Loading

Sediment loading of silts, clays, and sands were permanently reduced by at least 75 percent with the diversions of the White and Cedar Rivers, and potentially from the inception of Howard Hansen Dam (Dunne and Dietrich 1978; S. Madsen, pers. comm.). Annual suspended sediment discharge for the Duwamish is estimated at 1.7×10^5 metric tons per year based on daily measurements of suspended sediments taken in the mid 1960s (Dexter et al. 1981). Sediment sampling performed by GeoSea Consulting (1994) suggests that sand in the Duwamish River is becoming increasingly rare, and its removal (from dredging activities) may result in favoring the deposition of mud (silts and clays). What remains inconclusive in the study completed by GeoSea Consulting (1994) is how mud deposition is distributed as the result of riverine processes versus tidal activity. For instance, GeoSea Consulting (1994) conducted their sampling in only the dredged portion of the Duwamish River. The dredged channel resides at a lower elevation than the channel bench in the Duwamish River. Sediment transport initiated by the salt wedge is likely limited to the dredged portion of the channel, however the study performed by GeoSea Consulting (1994) does not and cannot differentiate between salt wedge deposition occurring inside the dredged channel versus on the channel bench. Additional research will be necessary for adequately assessing the sediment transport from tidal activity versus riverine processes in the Duwamish River.

Elliott Bay

Drift Cells

Schwartz et al. (1991) reported two drift cells along the shore of Elliott Bay—one cell along the shore of Magnolia Bluff and another segment of a drift cell between Alki Point and Duwamish

Head. Net shore drift along the southwest shore of Magnolia Bluff is dominated by westerly drift converging with shore drift from the northwest side of the bluff, forming a cuspate spit at West Point. The origin of the southwest Magnolia drift cell is immediately west of the Elliott Bay Marina. Westerly shore drift is indicated by a decreasing gradation in mean sediment size, and accumulation of sediment on the east side of groins and other drift obstructions. Mean sediment size generally decreases toward West Point (Schwartz et al. 1991).

Net shore drift between Alki Point and Duwamish Head is also dominated by a westerly drift that begins well south of Elliott Bay near Burien. Sediments reaching the south shore of Alki Point are transported west and north around the point. The substantial wave energy reaching this south shore is indicated by a broad wave-cut platform composed of sandstone and mudstone, which forms the foreshore along the south side of Alki Point. Sediment on the northwest side of the point is composed of cobble and pebble armor to poorly sorted sand and gravel. Mean sediment size decreases towards the northeast to moderately sorted sand, granule, and pebble along the bathing beach at Alki Park. Groins and bulkhead offsets along the north shore of Alki Point also indicate a net shore-drift in a northeasterly direction. Drift continues northward to Duwamish Head and is evidenced by an accumulation of well sorted coarse to medium sand on the west side of an observation promenade at the headland. Sand is transported eastward around Duwamish Head and builds an intertidal sand beach immediately north of Nest Side Park. The terminus of this westerly flow is on the bayward side of Duwamish Head, before reaching highly modified portions of the Elliott Bay waterfront (Schwartz et al. 1991).

Most of the Elliott Bay waterfront between Pier 91 and Duwamish Head has no appreciable net shore drift because of shoreline development. Much of this area has been modified by extensive filling, dredging, hillside regrading, and the placement of numerous overwater structures. Water depth and the obstruction of piers precludes any significant longshore transport. At present, the only source of sediment for shore drift is erosion of undefended fill material (Schwartz et al. 1991).

Stressors

The construction of overwater structures, armoring and other modifications of the original shoreline, and filling of the original river delta has eliminated net shore drift within Elliott Bay.

Historical Distribution

No historical information on drift cells was identified for the Elliott Bay area. Schwartz et al. (1991) reported a zone of divergence on the southeast shore of Magnolia Bluff near the present location of the Elliott Bay Marina. This drift cell of about 0.5 mi in length was directed eastward along the riprap shore of Smith Cove, building an intertidal sand and gravel spit where the shoreline abruptly turns north into the Pier 91 slip. The Pier 91 slip is a filled structure and an absolute barrier to shore drift (Schwartz et al. 1991). Presently, the Elliott Bay Marina acts as a barrier, likely eliminating this small drift cell.

Historically, it is likely that the drift around the Duwamish Head extended farther south down the western shore of Elliott Bay until the beach environment transitioned into the shallows and flats of the original river delta (see Figure 40). On the northeastern side of the bay, it is suspected that drift was complicated by south waves. Drift may have moved along the historical eastern shore in a northward direction from the present Queen Anne area to Smith Cove. South of Queen Anne, in the downtown waterfront areas, divergent drift south toward the river mouth and north toward Smith Cove probably occurred (H. Shipman, pers. comm.).

Reasons For Change From Historical Distribution

As reported, the modification of the shoreline, filling, and the construction of overwater structures have eliminated any appreciable net shore drift in Elliott Bay. It is likely that the direction of net shore drift along the sides of the bay, outside of the present waterfront area, has remained largely unchanged.

Data Gaps

Although several studies have examined the effects of changes in sediment dynamics on Elliott Bay and the Duwamish, numerous data gaps remain. Table 50 lists these data gaps.

Table 50: Data gaps for sediment dynamics

Data Gaps – Sediment Dynamics
▪ A comparison of the volume of silt, clays, and sands that currently are transported through the Howard Hansen Dam to sediment loading of these materials prior to the dam's inception would be useful. ▪ More definitive studies that address sediment transport from Elliott Bay to the Turning Basin in the Duwamish River are needed. ▪ Studies that address the impact of dredging activities on sediment transport from Elliott Bay to the Duwamish River are lacking. ▪ Calculation of sediment budget to determine if Duwamish River estuary habitats are stable or threatened by the loss of sediment supply.

Key Findings

Duwamish River

Dramatic alterations to flooding, stream flow, channel form, and sediment supply have significantly altered the sediment dynamics of the Duwamish River in ways that will continue to have long-term effects on its evolution. Large floods were primarily responsible for transporting and depositing large woody debris and sediments that regularly changed the configurations of the main active channel, side channels, and sloughs as well as providing abundant habitat for a variety of fish and wildlife. Today, the largest floods are a fraction of historical volumes and are allowed to occur only during the wettest time of the year (December through February). In conclusion:

- The sum total of these activities have resulted in a highly controlled river that has effectively eliminated the Duwamish River's ability to form and maintain channel complexity, such as lateral migration of the main channel, side channel and slough formation, and delta formation.
- Howard Hansen Dam has undoubtedly affected flooding in the Duwamish River, however its impact to sediment loading (silts, clays, sands) is largely unknown.

- There remains a question of how much contaminant transport occurs in the Duwamish River resulting from the tidal pumping of sediments landward. The assumption presented by ACOE (1997 p.36) implicates dredging practices for allowing the tide to migrate farther upstream than it had prior to channelization and dredging. This assumption may have some validity considering the potential combined effects of deepening the channel, reducing the watershed area by 70 percent, and reducing the freshwater discharge by 70 percent (ACOE 1997). Reducing the mean annual flow may have compromised the stream's ability to resist upstream migration of the high tides for greater time periods. Dredging the channel lowers the elevation of the channel bottom, which also makes it more accessible to a wider range of tides.
- The materials that compose the streambed may contain a greater concentration of sediments from Elliott Bay over a larger stretch of the Duwamish River if: (1) GeoSea Consulting's (1994) assertion is correct in that tidal activity dominates sediment deposition in the Duwamish Waterway; and (2) tidal activity is occurring farther upstream than it had previously.
- More conclusive studies are required in order to show: (1) if sediment transport occurs from Elliott Bay to the Duwamish River; (2) if and to what extent dredging operations increase sediment transport from Elliott Bay to the Duwamish River; and (3) the spatial distribution of marine sediment deposition and riverine deposition.

Elliott Bay

- Two drift cells are present along the shore of Elliott Bay—one cell along the shore of Magnolia Bluff and another segment of a drift cell between Alki Point and Duwamish Head.
- Net shore drift along the southwest shore of Magnolia Bluff is dominated by westerly drift converging with shore drift from the northwest side of the bluff, forming a cuspate spit at West Point. The origin of the southwest Magnolia drift cell is immediately west of the Elliott Bay Marina.
- Net shore drift between Alki Point and Duwamish Head is also dominated by a westerly drift that begins well south of Elliott Bay near Burien. Sediments reaching the south shore of Alki Point are transported west and north around the point.
- Most of the Elliott Bay waterfront between Pier 91 and Duwamish Head has no appreciable net shore drift because of shoreline development. Water depth and the obstruction of piers precludes any significant longshore transport. At present, the only source of sediment for shore drift is erosion of undefended fill material.

Salmonid Distribution and Use

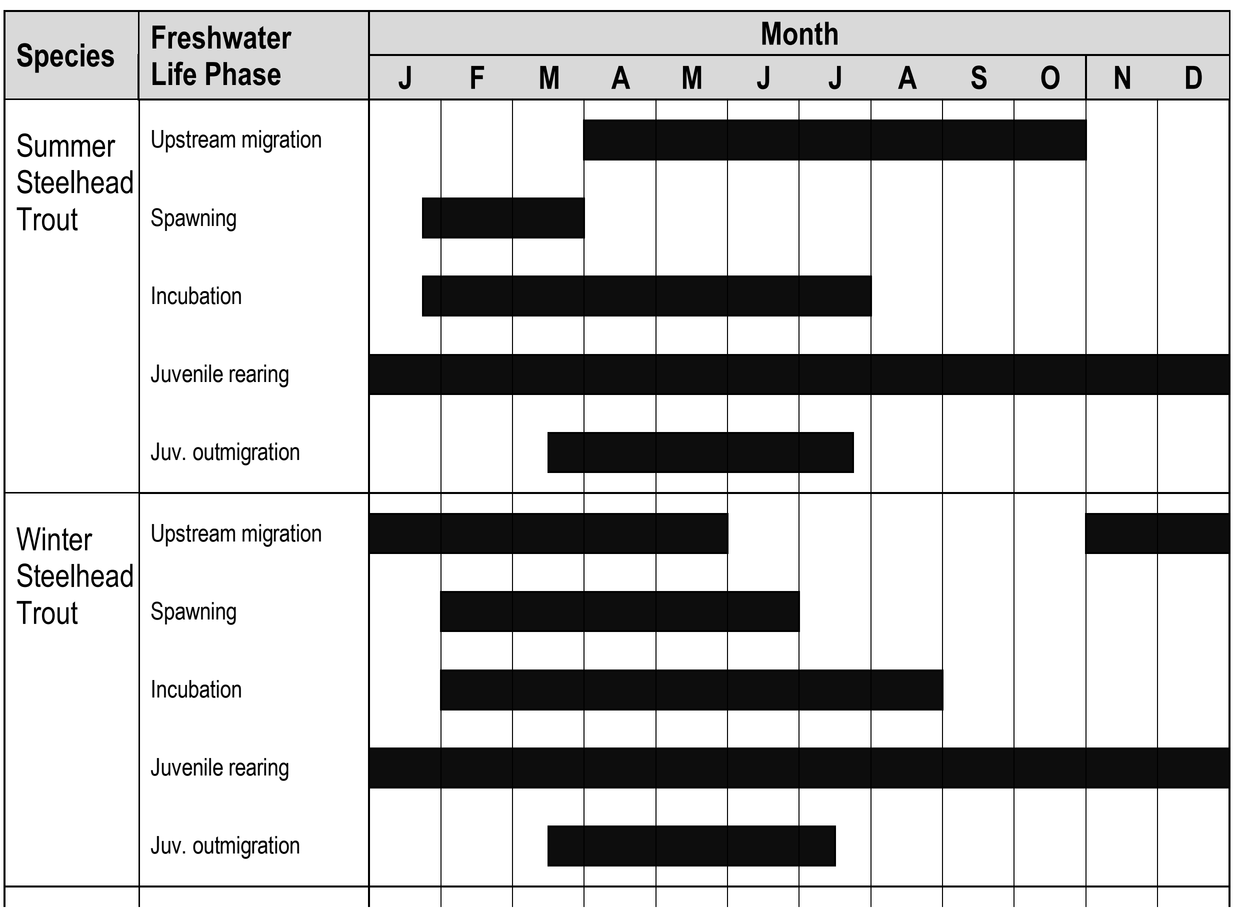
Eight species of native anadromous salmonids use the Duwamish Estuary, the Green River, and Elliott Bay:

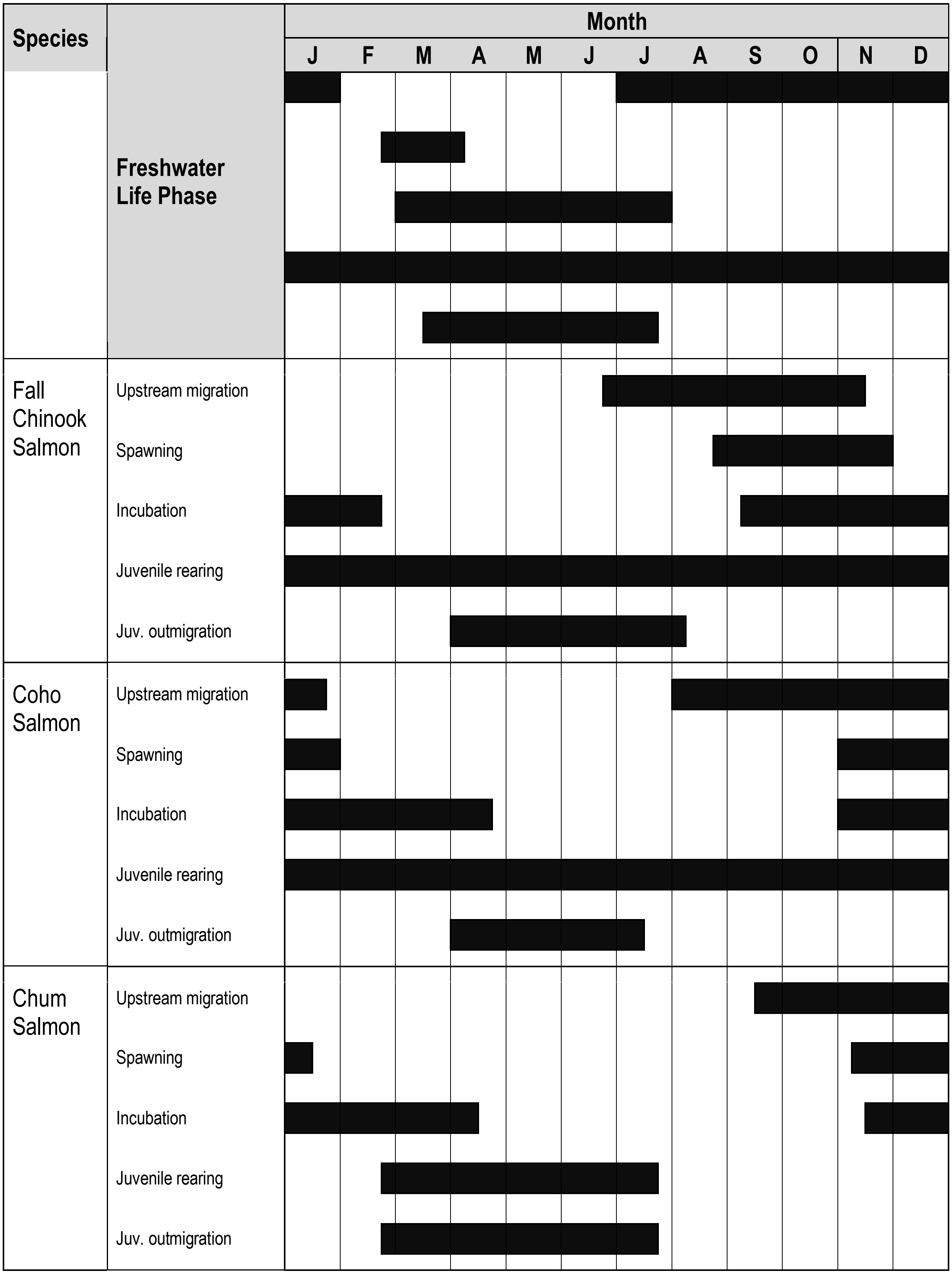
- Chinook salmon (*Oncorhynchus tshawytscha*)
- Coho salmon (*O. kisutch*)
- Chum salmon (*O. keta*)

- Pink salmon (*O. gorbuscha*)
- Sockeye salmon (*O. nerka*)
- Steelhead trout (*O. mykiss*)
- Sea-run cutthroat trout (*O. clarki*)
- Bull trout (*Salvelinus confluentus*)

Of these species, chinook and coho salmon and steelhead trout are common in the Duwamish basin, while pink and sockeye salmon, sea-run cutthroat trout, and bull trout are less common in the basin. Historically, pink and small chum salmon runs were in the river; large returns of chum have occurred in recent years. All eight species have been reported in Elliott Bay. Estuaries are particularly important to juvenile salmon for foraging, physiological transition to saltwater, and refugia. Adult salmon use estuaries briefly for staging, physiological transition to freshwater, and as a migratory corridor to spawning areas (Aitkin 1998). The general timing of juvenile and adult salmonids in the Green/Duwamish basin is presented in Table 51. However, recent studies (i.e., Warner and Fritz 1995; Taylor Associates unpublished data; WDFW unpublished data) indicate that timing of outmigration may begin earlier and extend later, exhibiting the variability in outmigration patterns that may be found in this system.

Table 51 Timing of anadromous salmonid migration in the Green/Duwamish River basin (from Grette and Salo 1986)




Species
Month
J F M A M J J A S O N D
Freshwater Life Phase
Fall Chinook Salmon
Upstream migration
Spawning
Incubation
Juvenile rearing
Juv. outmigration
Coho Salmon
Upstream migration
Spawning
Incubation
Juvenile rearing
Juv. outmigration
Chum Salmon
Upstream migration
Spawning
Incubation
Juvenile rearing
Juv. outmigration

Current Juvenile Use of the Duwamish and Elliott Bay Estuary

Juvenile Chinook Salmon

Fall chinook salmon that display the "ocean-type" juvenile migration pattern are found in the Duwamish/Green Rivers (Grette and Salo 1986). The ocean-type chinook salmon spends less than a year in freshwater before migrating to saltwater, while the "stream-type" chinook spends an extended juvenile period of one or more years in freshwater before migrating to saltwater. Ocean-type chinook salmon are the most dependent of all the salmon species on estuaries to complete their life cycle (Aitkin 1998).

Of the anadromous salmonids, Warner and Fritz (1995) found that juvenile chinook and chum were the most abundant juvenile salmon in the Duwamish Estuary, with roughly equal numbers, followed by juvenile coho salmon, pink salmon, steelhead trout, cutthroat trout, and bull trout (Table 52). Meyers et al. (1981) had similar results but found a much greater number of chinook juveniles than chum.

Downstream migration of chinook into the Duwamish Estuary has been observed as early as February (Warner and Fritz 1995). Weitkamp and Schadt (1982) also captured a few chinook in March and early April. However, increasing abundance of migrant chinook occurs later in April and early May (Bostick 1955; Weitkamp and Campbell 1980; Pearce et al. 1982; Taylor Associates unpublished data). Peak migration timing has been observed in early May (Pearce et al. 1982; Weitkamp and Schadt 1982), mid-May (Weitkamp and Campbell 1980, Warner and Fritz 1995), and late May or June (Bostick 1955; Parametrix 1984). Warner and Fritz (1995) found that the large pulse observed in May was concurrent with releases from the Soos Creek Hatchery. The abundance of migrating chinook in the Duwamish Estuary generally declines after June (Bostick 1955), although chinook are still captured through August and September (Weitkamp and Schadt 1982; Warner and Fritz 1995) (Table 51). Taylor Associates (in prep.) continued to capture unclipped juvenile chinook as late as October at Kellogg Island and Terminal 5 in 2000.

The distribution of juvenile chinook salmon in the Duwamish Estuary may be associated with the limited amount of natural habitat remaining in the waterway. Warner and Fritz (1995) found the greatest catch over shallow, sloping, soft mud beaches, and these sites produced double the catch ratios of sites with sand, gravel, or cobble substrates♣. Additionally, this study collected numerous benthic crustaceans and small shrimp at mud habitats, suggesting a higher productivity in comparison to sites with other substrates. This study also found the highest densities of juvenile chinook salmon in the upper estuary at RM 7.5. This area is a relatively large natural shoreline with intertidal flats and emergent vegetation (Tanner 1991). Modest densities were observed at the Turning Basin (RM 5.2), just downstream of RM 7.5 (Warner and Fritz 1995). These areas are also natural shorelines characterized by intertidal mudflats with some marsh vegetation. Steady decreases in juvenile chinook densities were observed downstream of the Turning Basin, with the exception of the most-downstream station at Kellogg Island (RM 1.6). At this station, densities increased to near those found at the Turning Basin (Warner and Fritz 1995). Kellogg Island was formed by extensive fill placements, but includes remnants of two historical channels and has a densely vegetated riparian zone and intertidal wetlands. These represent a majority of the remaining intertidal wetlands in the Duwamish Estuary (Simenstad et al. 1991). Meyer et al. (1981) found that juvenile chinook salmon were associated with both nearshore and offshore areas, but tended to move inshore at night and tended to move offshore with increasing size.

Table 52 The number of juvenile salmonids collected in the Duwamish Estuary (Warner and Fritz 1995)

Species	Number Collected
Chinook salmon	1,966
Chum salmon	2,190
Coho salmon	520
Pink salmon	14
Steelhead trout	31
Cutthroat trout	11
Bull trout	1*

Limited data on effort was provided. Two beach seine sets at each of 9 stations were conducted once or twice a week from February 18 through September 7.
*The single bull trout observed was an adult, not a juvenile.

Cordell et al. (1997) found that juvenile chinook fed on taxa that occurred in lower intertidal sediments or in the water column of the Duwamish Estuary. The diet of juvenile chinook salmon consisted mainly of dipteran flies, *Corophium* and *Eogammarus* amphipods, mysid shrimp, and fish larvae. Polychaete worms and *Daphnia* spp. were also consumed. Bivalve siphons, which are not commonly found in juvenile chinook diets, were abundant in diets on several occasions in the estuary. The study did not determine whether chinook fed preferentially on these prey or consumed them because other taxa were scarce. Meyer et al. (1981) had similar results, with gammarid amphipods (*Corophium* and *Eogammarus*), calanoid copepods, and dipteran flies as the most important prey categories. In examining diel differences, Meyer et al. (1981) found that gammerid amphipods, particularly *Corophium salmonis*, were consumed more at night than during the day and chironomid flies were consumed more during the day.

Although juvenile chinook salmon are present in the Duwamish Estuary over an 8-month period, catch data show an abrupt increase in smolts in mid-May followed by an equally abrupt decrease. This indicates that most of the fish represented in the pulse of abundance were not in the estuary for more than 2 weeks (Warner and Fritz 1995). Mark-and-recapture studies conducted by Weitkamp and Schadt (1982) showed similar results with most chinook remaining in the waterway for about two weeks. The longest individual residence was 24 days. Mark-and-recapture studies conducted by Bostick (1955) indicated that all chinook spent at least 1 week in the estuary, half spent 2 weeks, and two recaptured fish spent 6 weeks in the Duwamish Estuary.

After chinook outmigration peaks in the Duwamish Estuary, increasing abundances of chinook have been observed in Elliott Bay, but only through the summer months. Weitkamp and Schadt (1982) collected juvenile chinook by purse seine in Elliott Bay beginning in mid-May, but none were captured after late June. Taylor et al. (1999) found the greatest number of juvenile chinook at Terminal 5, located immediately west of Harbor Island, in mid-May, and at Pier 91, located 4 mi north of the Duwamish, in early June. Very few were observed at either location by early August. Parametrix (1984) observed juvenile chinook at Elliott Bay sampling stations in mid-June. Beamish et al. (1998) sampled salmonids throughout Puget Sound in 1997. Consistent with studies conducted within the bay and with evidence of early outmigration, this study sampled only two age-0 chinook in April and May, whereas in July and September they collected over 1,000 chinook. The study observed that chinook and chum salmon remain in Puget Sound through fall and winter.

Juvenile Chum Salmon

Chum salmon are highly estuary dependent, second to chinook in this dependence among the anadromous salmonids (Aitkin 1998). Consistent with their estuarine requirements, juvenile chum salmon also appear to be second to chinook in abundance and use of the Duwamish Estuary (Table 52). Warner and Fritz (1995) found juvenile chum from late February to mid-July, with the bulk of fish migrating through the estuary earlier than chinook. This study found three peaks in abundance: a moderate peak in late March, followed by a maximum peak in late April, followed by another lesser peak in late May. This timing generally followed high-water events during the winter and spring. Meyer et al. (1981) found two peaks in abundance: a lower peak in late April and a higher peak in early May. The maximum peak was associated with the release of 750,000 hatchery chum fry from Crisp Creek, a tributary of the middle Green River. Taylor et al. (1999) found only one peak in abundance in the estuary, that in late April.

Limited data on the distribution of juvenile chum salmon in the Duwamish Estuary are available. Warner and Fritz (1995) found the greatest catch over shallow, sloping, soft mud beaches, and these sites produced double the catch ratios of sites with sand, gravel, or cobble substrates. Additionally, this study collected numerous benthic crustaceans and small shrimp at mud habitats, suggesting a higher productivity in comparison to sites with other substrates. This study also reported the highest catch of juvenile chum salmon at the Turning Basin. Meyer et al. (1981) sampled only two sites, but did find that juvenile chum were highly oriented toward shallow shoreline areas. They were rarely captured in mid-channel habitats.

Cordell et al. (1997) and Meyer et al. (1981) have studied the diets of juvenile chum salmon in the Duwamish Estuary. They found that prey items were similar to those for chum in other estuaries in the Pacific Northwest and suggest that the species is opportunistic, feeding on a variety of epibenthic and pelagic invertebrates. Cordell et al. (1997) found that juvenile chum salmon in the Duwamish Estuary feed primarily on epibenthic harpacticoid copepods and *Corophium* amphipods. Calanoid copepods and dipteran insects were also consumed. The study found that the epibenthic harpacticoids—*Leimia vaga*, *Tachidius discipes*, and *Microarthridion littorale*—have not been previously observed as major constituents of juvenile chum diets, but they should provide good prey resources because of their size and abundance. The study also reported strong evidence that juvenile chum outmigrating through the Duwamish Estuary can find alternatives to epibenthic prey in planktonic crustaceans. They noted a complete dominance of planktonic cladocerans (*Daphnia* spp.) and calanoid copepods (*Eurytemora americana*) in the diets of several groups of chum examined. Meyer et al. (1981) found the same items in the diet of juvenile chum, but found somewhat different proportions compared to Cordell et al. (1997).

Meyer et al. (1981) found that chironomids were consumed by over 60 percent of fish examined but calanoid copepods were the dominant prey consumed, contributing 54 percent of all prey items enumerated and 40 percent of the total biomass.

Sample catches of juvenile chum salmon have declined fairly rapidly following peaks, like chinook catch rates after a peak. This suggests that individual fish were moving through the estuary in the space of a few days, but were replaced sporadically by a continual influx of fish from upstream (Warner and Fritz 1995). Mark and recapture studies conducted by Weitkamp and Schadt (1982) found similar results with most chum remaining in the waterway for about 1 week. Taylor et al. (1999) found chum juveniles over the smallest time period in the estuary, while fish were observed throughout the sampling period at stations located in the East Waterway and Elliott Bay, suggesting a rapid migration out of the estuary to saltwater.

Limited data from Elliott Bay indicate that juvenile chum salmon remain in the bay through the summer before outmigrating to other portions of Puget Sound and the ocean. Taylor et al. (1999) found juvenile chum at Terminal 5, located immediately west of the Harbor Island, from early April through late June, peaking in early April. The same study found juvenile chum at Pier 91, located 4 mi north of the Duwamish mouth during the same period but peaking in late April. The study found no chum by early August. Parametrix (1984) observed juvenile chum from mid-April through late May at several stations in Elliott Bay. Larger chum were observed in purse seine samples collected farther offshore, indicating the continuous migration out of the area beginning at sizes of about 75 mm in length. Juvenile chum were observed from early May through June in Commencement Bay (Meyer et al. 1981), and April through mid-June in the Nisqually Delta (Pearce et al. 1982).

Juvenile Coho Salmon

Juvenile coho salmon do not appear to be as estuary dependent as chinook or chum salmon, but have been found to reside in estuaries for a few days to a few weeks (Aitkin 1998). Life history strategies regarding estuarine residence vary widely (Warner and Fritz 1995). Substantially fewer juvenile coho salmon use the Duwamish Estuary compared to the number of chinook and chum salmon. Studies conducted in the waterway found coho capture rates between 5 and 25 percent of chinook capture rates (Warner and Fritz 1995, Meyer et al. 1981) (Table 53). Warner and Fritz (1995) found juvenile coho in the waterway from mid-February to mid-June, peaking in early May. Similar results were found by Meyer et al. (1981), although two peaks in coho abundance were observed—one in early May and another in early June (Table 52).

Cordell et al. (1997) examined a few juvenile coho in their study and discovered that the diet consisted almost entirely of crustaceans, over 80 percent of which were benthic amphipods. Meyer et al. (1981) found that gammarid amphipods and insects were the most important prey of coho. *Corophium salmonis* was the most important species followed by *Eogammarus confervicolus*. Of the insects, the most important were adult and larval chironomids. Insects were consumed primarily during the day while some crustaceans, such as the mysid shrimp and cumaceans, were eaten exclusively at night. *Corophium salmonis* was particularly important, consumed both day and night.

Very few data are available on the distribution of coho salmon in the Duwamish Estuary. This may be because of a relatively short residence time for the species. Meyer et al. (1981) suggested that juvenile coho probably move rapidly through the waterway as evidenced by their rapid increase and decrease in abundance. In limited investigations conducted in Elliott Bay, coho salmon were seldom observed (Parametrix, Inc. 1984). Similar findings were observed in the Nisqually Delta, where coho juveniles were only briefly observed from late April through late June (Pearce et al. 1982).

Other Juvenile Salmonids

Very few juvenile steelhead, sea-run cutthroat trout, and pink salmon have been observed in the Duwamish Estuary. Juvenile sockeye salmon and bull trout have not been observed in recent studies (Warner and Fritz 1995; Parametrix 1984; Meyer et al. 1981). Although steelhead populations spawn in the Green River (Grette and Salo 1986), juvenile steelhead do not appear to use estuaries for rearing (Aitkin 1998). Most sea-run cutthroat trout also pass rapidly through estuaries and inhabit shallow coastal waters. However, some sea-run cutthroat, both smolts and adults, are known to reside in estuaries and feed on outmigrating salmonid fry. Pink salmon have an affinity for saltwater as well, moving directly to the ocean and rearing in shallow shoreline areas (Aitkin 1998). The spawning populations of both sea-run cutthroat trout and pink salmon in the Duwamish/Green River are believed to be very small (Warner and Fritz 1995).

Juvenile pink salmon have a rare occurrence in the Duwamish Estuary, but Weitkamp and Schadt (1982) found a high abundance in Elliott Bay in late-April and a few in May and June. These fish may have come from a different river basin. Studies evaluating juvenile steelhead, cutthroat trout, sockeye salmon, and bull trout in Elliott Bay have not been identified.

Current Adult Use of the Duwamish Estuary and Elliott Bay

Fall Chinook Salmon

Green/Duwamish River fall chinook salmon migrate through the Duwamish Estuary from late June through mid-November, peaking between late September and late October (Grette and Salo 1986) (Table 51). Three stocks of chinook are present in the basin—a hatchery stock that is descended from a wild run; the Green/Duwamish stock, which spawns throughout the basin; and the Newaukum Creek stock, which spawns in this middle tributary of the Green River. The Green/Duwamish and Newaukum Creek stocks are considered "natural stocks," defined as naturally spawning fish that are descended from both wild and hatchery fish (WDFW and WWTIT 1994).

The run of fall chinook salmon in the Green/Duwamish River over the past 30 years is presented in Table 53. From 1968 to 1998 the estimated run of fall chinook salmon in the Green/Duwamish River ranged from 12,750 in 1982 to 40,508 in 1989 and averaged 20,900 fish. Run size tended to be higher during recent years (1983 to 1998) compared to earlier years (1968 to 1982), indicating that the downward trend common to other Puget Sound stocks is not evident in the Green/Duwamish basin (WDFW unpublished data). According to the Washington Department of Fish and Wildlife (WDFW and WWTIT 1994), the status of the Green/Duwamish stock is healthy based on recent escapement levels. The average escapement for the past 20 years is 6,153, with the minimum escapement of 1,804 occurring in 1982 and the maximum escapement of 11,512 occurring in 1989. The escapement goal set for this stock by WDFW is

5,800 (WDFW and WWTIT 1994). Escapement goals have been reached in 12 of the last 30 years and in 7 of the last 10 years (1988 to 1997). However, these are not necessarily wild or natural fish; the chinook runs in the Green are significantly supplemented by hatcheries.

The status of the Newaukum Creek stock is also considered healthy although there were sharp declines in escapement in 1990 and 1991. No escapement goals have been set for this stock by WDFW. The escapement ranges from 285 to 2,968, with an average of 1,600 for the years 1987 to 1991 (WDFW and WWTIT 1994).

Chum Salmon

Green/Duwamish chum salmon migrate through the Duwamish Estuary from mid-September through December with peaks occurring in November (Table 52). Two stocks of chum salmon are present in the basin—a small naturally spawning stock composed of fish with wild and hatchery origins, and a hatchery stock released from a hatchery on Crisp Creek. The hatchery stock is a mixture of wild descendants and a stock from Hood Canal (WDFW and WWTIT 1994).

The status of the naturally spawning population of chum salmon in the Green/Duwamish River is unknown. Over the past 30 years, the run has been so small that WDFW has not made quantitative estimates of run size. However, over the past 3 years, chum salmon runs in excess of 10,000 fish have returned to the Green River (T. Cropp, pers. comm.). Most of these fish are believed to be of hatchery origin and it is not clear why returns have been so high in recent years. The status of the Crisp Creek hatchery stock is considered healthy, but no escapement goals have been set by WDFW (WDFW and WWTIT 1994).

Coho Salmon

The run of coho salmon in the Green/Duwamish River over the past 30 years is presented in Table 53. Green/Duwamish coho salmon migrate through the Duwamish Estuary from August through late January with peak runs from mid September to late October (Table 51). There are two stocks of coho salmon in the Green/Duwamish basin—Soos Creek and Newaukum Creek; both are a mixture of wild and non-native hatchery fish. The Soos Creek stock is considered healthy, but the Newaukum Creek stock is depressed.

Table 53 Run size of chinook salmon, coho salmon, and steelhead trout in the Green/Duwamish River from 1966 to 1998 (WDFW unpublished data)

Year	Chinook	Coho	Winter Steelhead
1966	NA	112,038	NA
1967	NA	27,694	NA
1968	13,950	118,017	NA
1969	16,038	80,532	NA
1970	30,152	125,818	NA
1971	20,344	57,807	NA
1972	14,522	24,437	NA
1973	13,984	27,922	NA
1974	15,267	65,555	NA
1975	14,224	76,031	NA
1976	14,144	63,511	NA
1977	18,399	126,645	12,614
1978	16,011	48,902	12,056
1979	29,183	63,639	13,767
1980	28,800	87,335	11,561
1981	21,689	67,911	8,436
1982	12,750	82,213	7,815
1983	25,244	119,580	10,122
1984	12,392	98,689	17,301
1985	19,034	82,748	15,185
1986	19,698	119,539	13,211
1987	28,087	101,680	10,070
1988	23,045	115,180	5,719
1989	40,508	95,905	5,783
1990	35,644	127,574	3,071
1991	22,219	65,614	5,282
1992	18,546	51,213	4,174
1993	13,249	44,930	3,491
1994	17,769	112,170	4,945
1995	23,119	48,142	4,644
1996	28,068	28,872	NA
1997	22,792		3,031
1998	20,366		4,507

From 1966 to 1995 the estimated run of coho salmon in the Green/Duwamish River ranged from 27,964 in 1967 to 127,574 in 1990, and averaged 81,420 fish. As for chinook, run size of coho salmon has tended to be higher during recent years (1981 to 1995) compared to earlier years (1966 to 1980), indicating that the downward trend common to other Puget Sound stocks is not evident in the Green/Duwamish basin (WDFW unpublished data). According to WDFW (WDFW and WWTIT 1994), the status of the Green/Duwamish stock is healthy based on escapement levels. The average escapement for the past 20 years is 6,153, with the minimum escapement of 1,804 occurring in 1982 and the maximum escapement of 11,512 occurring in

1989. The escapement goal set for this stock by WDFW is 5,800 (WDFW and WWTIT 1994). Escapement goals have been reached in 12 of the last 30 years and in 7 of the last 10 years (1988 to 1997).

Pink Salmon

Green River pink salmon were characterized as extinct from this basin by Williams (1975). Additionally, no mention of a pink salmon stock was made in SASSI (WDFW and WWTIT 1994). More recently, Fuerstenberg (In Progress) was unable to locate reports of pink salmon present in the Green River basin. However, recent personal observations by Green River Technical Advisory Group members have indicated the presence of pink salmon in low numbers in the mainstem Green River. Adults have been observed as far upstream as the confluence with Burns Creek (RM 38.0) and an adult male carcass was observed in 1999 at RM 34.0. It is not clear if these are strays from other basins attempting to recolonize the Green River or remnant fish from the historic native population. Currently, the stock status for this species is unknown, but because of the low numbers present is probably depressed. These observations have been in odd number years only and the stock is believed to return in odd numbered years only.

Steelhead Trout

The run of steelhead trout in the Green/Duwamish River over the past 30 years is presented in Table 53. The Green/Duwamish basin contains both winter- and summer-run steelhead trout, with the winter run the larger of the two. Winter-run steelhead migrate from November through May (Table 51) and are composed of both hatchery and wild stocks. Hatchery fish tend to migrate through the estuary early, peaking in December and January, while native wild runs migrate later with peaks from late February through April. Summer-run steelhead migrate through the Duwamish Estuary from April through October and are composed almost entirely of a hatchery stock. Peak migration periods are also bimodal, occurring in June and July and again in late September and October (T. Cropp, pers. comm.). A small number of wild or natural summer-run steelhead also exist in the basin (WDFW and WWTIT 1994). Unlike Pacific salmon, steelhead do not always die after spawning. Repeat spawners have been found to compose from 0 to almost 20 percent of the returning wild adults. Adults that survive spawning migrate downstream soon after spawning, generally appearing in the estuary from March through May (T. Cropp, pers. comm.).

During 1977 to 1998, the estimated run of hatchery and wild winter steelhead in the Green/Duwamish river ranged from 3,031 in 1997 to 17,301 in 1984 and averaged 8,418 fish. Steelhead populations in the basin have declined over the past 21 years, with the average run from 1987 to 1998 at about 40 percent (4,974 fish) of those from 1977 to 1986 (12,207 fish) (WDFW, unpublished data).

Despite the decline, the status of the Green/Duwamish wild stock is considered healthy based on escapement levels. The escapement of wild winter-run steelhead averaged 1,954 fish for the years 1978 through 1998, with a range of 944 to 2,778. The escapement goal of 2,000 fish has been reached or exceeded in 8 of the past 20 years and WDFW considers the stock healthy. The summer-run hatchery stock is not native to the basin and was first planted in 1965. The stock is considered healthy but has no escapement goals because the species is managed for recreational harvest (WDFW and WWTIT 1994).

Sea-run Cutthroat Trout

Sea-run cutthroat trout are present in the Green/Duwamish basin, but little is known about this species. The run is apparently small compared to the runs of other salmonids in the basin as well as compared to other streams in northern Puget Sound. Spawning migration through the estuary occurs from July through January, peaking in October and November (Grette and Salo 1986). Warner and Fritz (1995) captured spawned-out adults in the estuary in February. Very few juvenile or adult cutthroat have been captured in other salmonid studies conducted in the estuary (Meyer et al. 1981, Weitkamp and Campbell 1980, Weitkamp and Schadt 1982). Data are insufficient to assess the current status of the stocks.

Bull Trout

Both bull trout and Dolly Varden char have occasionally been reported in the Duwamish Estuary; the two species are very difficult to distinguish from one another. Bull trout are not believed to spawn in the Green/Duwamish basin, but have been observed in the waterway (T. Cropp, pers. comm.). Warner and Fritz (1995) found one adult bull trout in the Duwamish Estuary in late May feeding on juvenile chinook salmon, which were abundant at the time. The study could not determine whether the char was native to the watershed or was an opportunistic marine predator. Taylor Associates (B. Taylor, pers. comm.) found 8 char near the Turning Basin in September 2000. Grette and Salo (1986) reported that sea-run Dolly Varden char were present in the Green River, but that little was known about the distribution, population, or stock status in the basin. At the time of the Grette and Salo study (1986), all anadromous char in Puget Sound were considered to be Dolly Varden. However, this assumption is no longer valid, as anadromous forms of bull trout are now known to utilize Puget Sound, including the Duwamish River (C. Tanner, USFWS, personnal communication).

Historical Use of the Duwamish Estuary by Anadromous Salmonids

Early historical records of fish resources of the Duwamish Estuary are limited. Species that are believed to have been present in the basin prior to 1911 are spring and fall chinook, coho, sockeye, pink, and chum salmon; winter-run steelhead, sea-run cutthroat, Dolly Varden char, and bull trout. It is known that anadromous salmonids were abundant because the Duwamish Tribe and early settlers operated weirs and other capture devices for salmon in the lower river and estuary. Spring chinook salmon were known from the White River, a major tributary to the Duwamish Estuary that was diverted to the Puyallup River basin in 1911 (USACOE 1997).

Estimates of historical juvenile salmonid use in the Duwamish Estuary have not been made. However, early in the 20th century, prior to development, the extensive mudflats, saltmarsh, floodplain, and delta likely provided substantial rearing habitat for chinook, chum, and pink salmon, the species most associated with estuarine use (USACOE 1997). In addition to juvenile rearing, Chapman (1982) estimated that adult chinook, chum, and pink salmon spawned in the lower 28 mi of the river. The study estimated that 299 chinook, 6,214 chum, and 10,950 pink salmon spawned in this reach, which currently provides little spawning habitat. Diking and channel confinement have resulted in streambed scour, which has greatly altered streambed dynamics.

Estimates of historical total adult run size in the Duwamish basin are over 22,000 chinook salmon, 32,000 coho salmon, 121,000 chum salmon, 233,000 pink salmon, 6,500 steelhead, and 1,125 cutthroat trout. Sufficient data were not available to make historical estimates for sockeye salmon, Dolly Varden, or bull trout (USACOE 1997).

Reasons for Changes in Salmonid Abundance

Changes in adult salmonid populations that can likely be linked to the development of the estuary include the substantial elimination of sockeye and spring chinook salmon runs from the Green/Duwamish basin. Prior to 1911, the White River discharged to the Duwamish River, after which it was diverted to the Puyallup River for flood-control purposes. Prior to 1916, the Black River flowed from Lake Washington to the Duwamish. The Cedar River also flowed into the Black River, connecting this watershed to the Duwamish as well. In 1916, the elevation of Lake Washington was lowered by the construction of the Ship Canal. This caused the Black River to cease flowing, and the Cedar River was later routed into Lake Washington (Grette and Salo 1986). Cumulatively, these changes reduced the estuary's watershed by 71 percent (Blomberg et al. 1988). Sockeye salmon, rearing only in the lakes of the Black River basin (Lakes Washington and Sammamish), and spring chinook, found in the White River basin, were forced to bypass the Duwamish Estuary, entering their watersheds through Commencement Bay and Lake Washington (Warner and Fritz 1995). Pink salmon have not returned to the Green River in large numbers since the 1930s, although it is not known whether this was caused by the diversions or by channel armoring in the lower river (Warner and Fritz 1995); Grette and Salo 1986).

Development of the estuary to its present characteristics has eliminated over 97 percent of the former area of shallows, flats, and tidal marshes. Tidal swamp habitat has been completely eliminated. The significant reduction in estuarine intertidal wetlands has diminished the production of invertebrate food organisms important to juvenile salmonids migrating through the estuary. In addition, loss of the complex mosaic of marshes, flats, and channels has diminished available refugia; and circulation changes have modified the stretches of the estuary used for physiological transition (Blomberg et al. 1988). Blomberg et al. (1988) reports that the overall outcome is probably shorter residence times and lower growth in the estuary, resulting in a net lower survival of the Duwamish salmon populations compared to less developed estuaries and watersheds. Nonetheless, WDFW reports that chinook salmon released from the Green River hatchery display a higher marine survival rate than any other hatchery stock in Puget Sound (T. Cropp, pers. comm.).

Stressors

As discussed in earlier sections, studies have reported several potential stressors that juvenile salmonids may face upon traversing the Duwamish Estuary and Elliott Bay:

- The highly modified stream channel and nearshore of the estuary and bay may limit the feeding and refuge opportunities of juvenile salmonids as they traverse the area (see Shoreline Armoring).
- Modifications in migratory behavior upon encountering overwater structures may occur such that delays in migration or increased susceptibility to predation may result (see Overwater Structures).

- Contaminant investigations in the estuary have found that juvenile salmon bioaccumulate several organic contaminants. Biochemical indicators also suggest that physiological impacts may be occurring as a result of their exposure (see Sediment Contamination).

Data Gaps

Numerous studies have been conducted on salmonid use in the Duwamish Estuary, Elliott Bay, and other areas of Puget Sound. Much is understood regarding the general migratory behavior, timing, distribution, and feeding habits of juvenile salmonids, but key questions remain, particularly with regard to restoration issues and optimal habitats and the quantitative effects of degraded habitats. The following data gaps are summarized in Table 54:

Table 54 Data gaps for salmonids

▪ **Data Gaps – Salmonids**
▪ Most estuarine and nearshore habitat studies have been conducted in developed areas; relatively little information has been collected in less- or non-degraded habitats. The responses of juvenile salmonids in developed areas may not be representative of natural estuaries. There is a need to study and document juvenile salmonid behavior in undisturbed areas to establish a baseline. ▪ There is a lack of quantitative sampling data for juvenile salmonids' use of nearshore and open beach habitats around Elliott Bay. ▪ Juvenile salmonids grow rapidly, but there are no data on possible food limitations in the Duwamish Estuary and Elliott Bay, nor comparison data from undisturbed estuaries and bays (i.e., on the growth potential of these fish in the absence of the high degree of habitat disturbance evident in the area). ▪ More data are needed regarding predation on juvenile salmonids in the estuary and the effects of highly modified habitats on survival. The interactions between overwater structures and shoreline hardening and salmonid predation rates are not known. Habitat modifications that increase predation, or which offer a greater degree of protection and refuge, have not been well studied. A better understanding of physical separation that may or may not exist between juvenile salmonids and their predators is needed. ▪ The role of shoreline armoring and other upland development practices, such as modifying riparian zones, on juvenile salmonids is poorly understood. ▪ Additional information is needed on the presence and habitat utilization of native char. ▪ There is also a need for the long-term collection of quantitative data on residence time and condition indices, and the same from relatively undisturbed estuaries. These data, collected annually, would provide the necessary baselines to better evaluate future development projects for their impacts on juvenile salmon habitats, and would guide the selection and construction of restoration sites in the estuary. ▪ The long-term effects of bioaccumulation and toxicological pathways through the food chain have not been assessed. ▪ Estuarine carrying capacity for the Duwamish and Elliott Bay need to be addressed. There is a lack of quantified information on habitat carrying capacity for juvenile salmonids.

Key Findings

- Eight species of anadromous salmonids use the Duwamish Estuary, Green River, and Elliott Bay. Chinook and coho salmon and steelhead are common, while pink and sockeye salmon, sea-run cutthroat trout, and bull trout are much less common.. Small runs of chum salmon also occur, with larger runs in recent years.
- Juvenile chinook and chum salmon are highly dependent on estuarine habitats, as evidenced by studies of residence time, diets, and behavior. During their downstream migration, these species enter the estuary during the late winter/early spring and most individuals appear to spend 1 to 2 weeks in the estuary before entering Elliott Bay. They are, however, likely to be present in the estuary during at least eight months of the year. Less is known about residence times in the bay, but most have left the bay by the end of summer. The other salmonids are less abundant and do not appear as estuarine dependent as chinook or chum salmon.
- All of the juvenile salmonids in the estuary have been found to feed on gammarid amphipods, dipteran insects, and harpacticoid copepods.
- Adult chinook and coho salmon runs in the Green River appear stable, with larger runs over the past 15 years compared to earlier years. Chum salmon runs have historically been small in the Green River, but over the past 3 years larger runs exceeding 10,000 fish have been observed. In contrast, winter steelhead runs have shown a steady decline over the past 30 years. Appreciable pink and sockeye salmon runs do not occur in the Green River.
- Sea-run cutthroat trout are present in the Green River, but little is known about the species.
- Bull trout have been reported in the river, but are not believed to spawn in the basin.
- Historically, it is believed that spring and fall chinook, coho, sockeye, pink, and chum salmon; winter run steelhead, sea-run cutthroat, Dolly Varden char, and bull trout used the basin.
- Changes in species composition and abundance can be linked to the development of the estuary. The substantial elimination of sockeye and spring chinook salmon runs are likely linked to the diversion of the Black and White Rivers early in the century. The substantial elimination of pink salmon may be due to diversions or channel armoring in the lower river.
- There is a general lack of sufficient ecological data to quantify the role of estuaries in the development and survival of juvenile salmonids. Many distributional studies have been conducted, but the links between habitat use, growth and survival, and armoring, industrial development, and other alterations to habitat and ecosystem processes and functions are limited in terms of ecosystem modeling and scientific monitoring.

Other Fin-Fish Distribution and Use

Duwamish Estuary

Non-anadromous fish species documented within the Duwamish Estuary are dominated by estuarine and marine species, with only a few freshwater species. This would be expected given the salinity profile of the estuary. At high tide, Warner and Fritz (1995) found fresh water at

RM 10.4, at all depths, but found fairly uniform salinities between 25 and 28 ppt from RM 7.5 to RM 1.6, at depths of 3 ft and deeper.

Matsuda et al. (1968), Miller et al. (1977), and Warner and Fritz (1995) have conducted resident fish surveys in the Duwamish Estuary, although information and data regarding specific distribution and uses of the estuary by different life stages are limited. Each of the surveys collected between 29 and 33 marine, estuarine, anadromous, and freshwater species. Table 55 presents the species and the numbers of fish collected in a recent beach seine survey conducted in 1994 (Warner and Fritz 1995). This table does not represent a complete list of species found in the Duwamish; for example, sturgeon also live there (T. Nelson, pers. comm.).

Shiner perch were the most abundant species collected in the estuary, but their presence was seasonal and associated with spawning runs. Shiner perch were not observed until beach seine sets in early May, but within 1 month their abundance was up to 4,000 fish per set. By mid-July, the ovoviviparous species gave live birth, multiplying the density of individuals by several fold. Their numbers declined throughout the late summer and were absent by November (Warner and Fritz 1995).

Pacific staghorn sculpin, snake prickleback, starry flounder, and Pacific sand lance were observed at abundances approaching those of chinook and coho salmon (Table 55) (Warner and Fritz 1995). Pacific staghorn sculpin and starry flounder are known to penetrate the lower reaches of streams and reside in very low salinities (Hart 1973). Starry flounder have been observed at the greatest abundance in the fall and winter, and are least abundant during the summer (Griggs 1979, Miller et al. 1977). Pacific staghorn sculpin are abundant throughout the year and are believed to be year-round residents (Stober and Pierson 1984). Very little information regarding the estuarine behavior of pricklebacks was identified. Pacific sand lance are one of the more abundant forage fish in Puget Sound and common inhabitants of shallow nearshore waters and estuaries. These four species, along with shiner perch and juvenile salmonids, made up over 99 percent of the fish collected in the estuary (Warner and Fritz 1995).

Stober and Pierson (1984) reported that species abundance and total abundance in the Duwamish Estuary exhibits considerable annual variation. Catch was generally lowest during the late fall and winter, increased markedly through the spring and summer, and peaked in the late summer and early fall.

Virtually no information exists regarding the historical, pre-development assemblage of demersal and resident fish in the Duwamish Estuary. Some comparisons can be made with surveys conducted in the 1960s and 1970s, but care is necessary since collection locations and sampling techniques differed. Earlier surveys conducted by Matsuda et al. (1968) and Miller et al. (1977) found that four or five demersal species dominated collections, a finding similar to that of Warner and Fritz (1995). However, Miller et al. (1977), using otter trawl gear, found a moderate to high abundance of Pacific tomcod and longfin smelt, while Warner and Fritz (1995) did not find these species. It is known that both species have decreased dramatically in Puget Sound over the past 20 years. The reasons for the declines are unclear. Similarly, English sole dominated earlier surveys, while only two were collected by Warner and Fritz (1995). This difference, however, may be due to different sampling locations, since Warner and Fritz (1995) did not sample below Kellogg Island (RM 1.6), while the earlier study collected fish into the East and West Waterways, near the mouth.

Table 55 Fish species collected in the Duwamish River in 1994 (Warner and Fritz 1995)

Common Name	Scientific Name	Number Collected
Anadromous Salmonids		
Chinook salmon	*Oncorhynchus tshawytscha*	1,966
Chum salmon	*Oncorhynchus keta*	2,190
Coho salmon	*Oncorhynchus kisutch*	520
Pink salmon	*Oncorhynchus gorbuscha*	14
Steelhead trout	*Oncorhynchus mykiss*	31
Cutthroat trout	*Oncorhynchus clarki*	11
Bull trout	*Salvelinus confluentus*	1
Sea Perch		
Shiner perch	*Cymatogaster aggregata*	15,659
Striped sea perch	*Embiotoca lateralis*	27
Pile perch	*Rhacochilis vaca*	6
Sculpins		
Northern sculpin	*Icelinus borealis*	12
Pacific staghorn sculpin	*Leptocottus armatus*	1,480
Sharpnose sculpin	*Clinocottus acuticeps*	3
Gunnels and Pricklebacks		
Snake prickleback	*Lumpenus sagitta*	2,159
Crescent gunnel	*Pholis laeta*	68
Saddleback gunnel	*Pholis ornata*	6
Penpoint gunnel	*Apodichthys flavidus*	9
Flatfish		
Starry flounder	*Platichthys stellatus*	1,178
English sole	*Pleuronectes vetulus*	2
Butter sole	*Isopsetta isolepis*	14
Other Marine Species		
River lamprey	*Lampetra ayresi*	6
Pacific herring	*Clupea pallasi*	37
Surf smelt	*Hypomesus pretiosus*	226
Threespine stickleback	*Gasterosteus aculeatus*	395
Bay pipefish	*Syngnathus griseolineatus*	12
Bay goby	*Lepidogobius lepidus*	2
Pacific sand lance	*Ammodytes hexapterus*	1,004
Freshwater Species		
Longnose dace	*Rhinichthys cataractae*	2
Largescale sucker	*Catastomus macrocheilus*	28

Common Name	Scientific Name	Number Collected
Prickly sculpin	*Cottus asper*	4
Redside shiner	*Richardsonius balteatus*	100
Northern pikeminnow	*Ptychocheilus oregonensus*	2
Mountain whitefish	*Prosopium wiliamsoni*	170

Elliott Bay

A substantially greater number of fish species have been documented in Elliott Bay compared to the Duwamish Estuary. Although no recent fish surveys were identified in Elliott Bay, extensive beach seine and otter trawl surveys were conducted at both West Point and Alki Point in 1975 and 1976. Over 80 species of fish were observed at the two locations, as presented in Table 56 (Miller et al. 1977). Other data sets may offer additional information, but were not reviewed for this report. These include Malins et al. (1980); WDFW unpublished data; and PSAMP data.

A similar species assemblage was observed at both Alki Point and West Point, with 75 total species identified at Alki Point and 72 species at West Point. In both areas, between 75 and 85 percent of the total number of fish were composed of five species, with shiner perch, English sole, and rock sole dominant in both areas. Tube-snout and striped sea perch were also dominant at Alki Point, while Pacific tomcod and ratfish were dominant at West Point.

At both West Point and Alki Point, the lowest values for abundance and species richness occurred during the late winter and early spring. At Alki, abundance and species richness increased during the spring and early summer, declined in late summer, then increased again through the fall. West Point had only a single abundance peak during the fall. Species richness increased in spring and peaked in summer, but declined throughout the remainder of the year.

Borton (1982) and Miller et al. (1977) found striking differences in abundance and species richness in fishes associated with eelgrass beds in the study area as opposed to fishes associated with sand substrates. Forty-one species were collected from eelgrass areas, but only 22 species were collected from sandy areas. The density of fish (fish per unit area of bottom) was also substantially higher in eelgrass by a factor of nearly 9 to 1. The most abundant eelgrass species included sand lance and shiner perch, while the shiner perch, English sole, and tomcod were dominant on sand. Several species were clearly eelgrass-associated and no species was more abundant on sand than in eelgrass. Abundance and species richness were also much higher in eelgrass than on sand.

Stressors

The stressors on resident marine fish in the Duwamish Estuary and Elliott Bay are not well understood. Very few studies have evaluated the interactions between channel and nearshore modifications and resident fish populations or behavior. Potential stressors for resident demersal fish are the bioaccumulation and subsequent toxicological effects of xenobiotic chemical compounds. As reported in the Sediment Contamination section, Johnson et al. (1994) has demonstrated that elevated concentrations of PAHs and PCBs occur in bile as metabolites of demersal fish species from the Duwamish Estuary. This study also found an increased incidence of reproductive impairment from English sole collected from urban areas. Several other studies have found that the prevalence of liver tumors and other liver conditions in English sole was highest in the Duwamish River (Malins et al. 1984, 1985; Krahn et al. 1987; Meyers et al. 1987, 1992, 1994). These studies suggest that physiological impacts are affecting the survival or reproduction of some demersal species in Elliott Bay. The extent of such impacts on the populations of these resident species is largely unknown.

Table 56 Fish species collected off Alki Point and West Point (Miller et al. 1977)

Common Name	Scientific Name	Total Number	
		Alki Point	West Point
Spiny dogfish	*Squalis acanthias*	1	9
Ratfish	*Hydrolagus colliei*	314	1,420
Pacific herring	*Clupea pallasi*	13	481
Chum salmon	*Oncorhynchus keta*	41	92
Pink salmon	*Oncorhynchus gorbuscha*	6	13
Coho salmon	*Oncorhynchus kisutch*	25	168
Chinook salmon	*Oncorhynchus tshawytscha*	34	24
Dolly Varden	*Salvelinus malma*	0	2
Rainbow trout	*Oncorhynchus mykiss*	1	0
Surf smelt	*Hypomesus pretiosus*	1	55
Longfin smelt	*Spirinchus thaleichthys*	0	2
Midshipman	*Porichthys notatus*	37	1
Northern clingfish	*Gobiesox maeandricus*	2	0
Pacific cod	*Gadus macrocephalus*	17	1
Pacific tomcod	*Microgadus proximus*	687	4,836
Walleye pollock	*Theragra chalcogramma*	47	18
Pacific hake	*Merluccius productus*	3	1
Red brotula	*Brosmophycis marginata*	0	1
Blackbelly eelpout	*Lycodopsis pacifica*	24	56
Tube-snout	*Aulorhynchus flavidus*	1,874	7
Threespine stickleback	*Gasterosteus aculeatus*	2	22
Bay pipefish	*Syngnathus griseolineatus*	35	1
Shiner perch	*Cymatogaster aggregata*	6,509	4,419
Striped seaperch	*Embiotoca lateralis*	2,164	119
Pile perch	*Rhacochilus vacca*	108	44
Northern ronquil	*Ronquilus jordani*	69	58
Wolf eel	*Anarrichthys ocellatus*	1	0
Snake prickleback	*Lumpenus sagitta*	10	79
Penpoint gunnel	*Apodichthys flavidus*	127	5
Crescent gunnel	*Pholis laeta*	21	0
Saddleback gunnel	*Pholis ornata*	26	3
Pacific sandlance	*Ammodytes hexapterus*	0	247

Common Name	Scientific Name	Total Number	
		Alki Point	West Point
Brown rockfish	*Sebastes auriculatus*	31	56
Sharpchin rockfish	*Sebastes zacentrus*	1	0
Copper rockfish	*Sebastes caurinus*	3	2
Quillback rockfish	*Sebastes maliger*	45	84
Redstripe rockfish	*Sebastes proriger*	15	2
Painted greenling	*Oxylebius pictus*	4	2
Whitespotted greenling	*Hexagrammos stelleri*	3	3
Padded sculpin	*Artedius fenestralis*	337	68
Scalyhead sculpin	*Artedius harringtoni*	0	1
Smoothhead sculpin	*Artedius lateralis*	5	0
Silverspotted sculpin	*Blepsias cirrhosus*	71	9
Roughback sculpin	*Chitonotus pugetensis*	162	69
Sharpnose sculpin	*Clinocottus acuticeps*	76	42
Buffalo sculpin	*Enophrys bison*	88	96
Northern sculpin	*Icelinus borealis*	9	0
Red Irish lord	*Hemilepidotus hemilepidotus*	14	1
Spotfin sculpin	*Icelinus tenuis*	77	0
Pacific staghorn sculpin	*Leptocottus armatus*	172	296
Grunt sculpin	*Rhamphocottus richardsoni*	1	1
Great sculpin	*Myoxocephalus polyacanthocephalus*	19	3
Manacled sculpin	*Synchirus gilli*	1	1
Sailfin sculpin	*Nautichthys oculofasciatus*	40	6
Tidepool sculpin	*Oligocottus maculosus*	19	27
Threadfin sculpin	*Icelinus filamentosus*	1	0
Slim sculpin	*Radulinus asprellus*	44	13
Tadpole sculpin	*Psychrolutes paradoxus*	0	1
Roughspine sculpin	*Triglops macellus*	1	0
Ribbed sculpin	*Triglops pingeli*	1	0
Cabezon	*Scorpaenichthys marmoratus*	6	2
Northern spearnose poacher	*Agonopsis emmelane*	14	5
Sturgeon poacher	*Agonus acipenserinus*	55	92
Gray starsnout	*Bathyagonus alascanus*	5	4
Spinycheek starsnout	*Bathyagonus infraspinatus*	0	6
Pygmy poacher	*Odontopyxis trispinosa*	64	7
Blacktip poacher	*Xeneretmus latifrons*	30	7
Bluespotted poacher	*Xeneretmus triacanthus*	69	31
Tidepool snailfish	*Liparis florae*	0	1
Pacific sanddab	*Citharichthys sordidus*	32	97

Common Name	Scientific Name	Total Number	
		Alki Point	West Point
Speckled sanddab	*Citharichthys stigmaeus*	72	56
Rex sole	*Glyptocephalus zachirus*	32	60
Butter sole	*Isopsetta isolepis*	0	5
Rock sole	*Lepidosetta bilineata*	1,381	1,639
Slender sole	*Lyopsetta exilis*	83	62
Dover sole	*Microstomus pacificus*	178	229
English sole	*Pleuronectes vetulus*	1,530	4,114
Starry flounder	*Platichthys stellatus*	8	32
C-O sole	*Pleuronichthys coenosus*	357	92
Hybrid sole	*Isopsetta ischyra*	0	1
Sand sole	*Psettichtys melanostictus*	10	26
Arrowtooth flounder	*Atheresthes stomias*	1	1
Flathead sole	*Hippoglossoides elassodon*	1	1
Total Number Individuals		**17,367**	**19,537**
Total Number Species		**75**	**72**

Data Gaps

Although the Duwamish Estuary and Elliott Bay have been fairly well studied, the focus has been on salmonid use as juveniles, and adult salmonid stock assessment. Gear types most effective at sampling non-salmonids (i.e., bottom and mid-water trawls, purse seines) have not been used in recent studies. Several data gaps regarding other fin fish species are apparent and identified in Table 57:

Table 57: Data gaps for other fin-fish species

Data Gaps – Other Fin-fish Species
▪ Stock assessments of demersal fish species are needed. Very little is known regarding the populations and movements of demersal species, particularly those candidates for ESA listing. Interactions of fish populations with oceanographic conditions, such as long-term temperature regimes and interactions with predators, are not clear.
▪ Existing data sets for demersal fish species have been collected by WDFW and the University of Washington, but have not been fully analyzed or published. The Muckleshoot Indian Tribe has not analyzed extensive beach seining data from 1995.
▪ Stock assessment of important forage fishes such as surf smelt and sand lance are lacking. Beach spawning habitats in the study area are not fully known and it is unclear whether discrete spawning populations exist or use specific beach habitats.
▪ An assessment of toxicological pathways through the food chain is needed.

Key Findings

- Non-anadromous fish species documented within the Duwamish Estuary are dominated by estuarine and marine species, with only a few freshwater species. Thirty-three species were observed in a recent survey dominated by shiner perch, staghorn sculpin, starry flounder, sand lance, and prickleback.
- In contrast, the fish assemblage in Elliott Bay is much larger; fish surveys have documented about 80 species. Dominant species include English and rock sole, Pacific tomcod, shiner and striped seaperch, tubesnout, and ratfish.
- The highest abundance and species richness occurs during the summer and fall with the lowest during the late winter and early spring.
- Studies have found striking increases in abundance and species richness in fish assemblages associated with eelgrass compared to sand substrates.

Shellfish Distribution

Current Distribution

Very little information on the distribution of shellfish in the study area was identified. Geoduck surveys in 1970 found a geoduck clam population in Elliott Bay south of West Point (Sizemore and Ulrich 2000). Stober and Pierson (1984) estimated the bed at approximately 190 acres and containing 610,000 clams. Goodwin (1973) used this information to calculate that 476 acres of suitable geoduck habitat may exist in Elliott Bay, which could support approximately 768,000 clams.

Historical Distribution

No information on historical shellfish populations was identified. However, since extensive flats and marshes historically existed in Elliott Bay and the Duwamish, it is reasonable to expect that they used to support densities of shellfish comparable to those in existing shellfish beds.

Data Gaps

Shellfish populations in Elliott Bay are presently not harvested because of high fecal coliform counts and industrial effluent inputs. However, the ability of shellfish to improve water quality by removing pollutants from the water column is unknown. The effects of this bioaccumulation on shellfish and other species are also unknown.

Key Findings

Limited data suggests that over 400 acres of suitable geoduck habitat may exist in Elliott Bay, which could support over 700,000 clams.